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Stress analysis of ground mounted signboards

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by

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ABSTRACT

A ground-mounted signboard consists of a frame made of aluminum, a front panel made of composite material and two aluminum posts running through half the length of the frame into the ground supporting the entire board. The wind speeds in Iowa are very high and these high winds may cause the frame to be stressed beyond the safe limit of the material causing failure in the frame. Hence, this project required performing stress analysis on the frame of the signboard to check the consistency of the design and recommend improvements to the design such that the frame can withstand wind speeds of up to 100 miles per hour (*mph*). The analysis was performed on two different signboard models, 50"x144"x12" and 122"x98"x12". These represent the widest and tallest models respectively. The stress analysis on these two models was carried out using finite element analysis software called ANSYS and based on the results obtained; recommendations were suggested for the design. The analysis was carried out in two phases. Initially reduced models of both the dimensional frames were generated and then were subjected to 100 *mph* wind pressure. A reduced model analysis was carried out as the cross-section of the frame was very complicated, and to obtain the wind loads acting on the frame a model with equivalent cross-sectional area and moment of inertia, as that of the original model would be sufficient. This analysis was used for foundation and anchor design. Subsequently, the analysis was carried out on the frames with actual cross-section and the results are presented.

CHAPTER 1
INTRODUCTION

1.1 Problem overview

The signboard, which has been analyzed in this work consists of a frame made of aluminum, front and back panels made of fiberglass and two aluminum posts running through half the length of the frame into the ground supporting the entire board. The wind speeds in Iowa are very high and these high winds cause the frame to be stressed beyond the safe limit of the material causing failure in the frame. Hence, this project was devoted towards performing stress analysis on the frame of the signboard and recommending improvements on the design such that the frame can withstand wind speeds of up to 100 *mph*.

The actual designing of the signboard was carried out based on the detailed drawings provided by ASI Signs Systems Inc. The frame of the board was an aluminum extrusion and the front and back panel sheets were made of fiberglass. Since, the signboards that ASI Signs manufactured were of various dimensions, the analysis was carried out on the widest and tallest models so that all of the other models with dimensions in-between could withstand high pressures caused by winds. Thus, the conclusions of this analysis can be extended to all models that were manufactured by the company assuring their safety.

The two-signboard models that analysis was carried out were of the dimensions 50"x144" (short and wide frame) and 122"x98" (tall and narrow frame) with the thickness being one foot for both the models. Two types of analysis were carried on these boards:

- The boards when mounted on the ground with posts
- The boards when mounted on the ground directly with anchors and bolts

Fig.1.1 shows an outline of 50"x144" dimensional ground mounted signboard using posts and Fig.1.2 shows an outline of a ground mounted signboard using bolts and anchors at various locations.

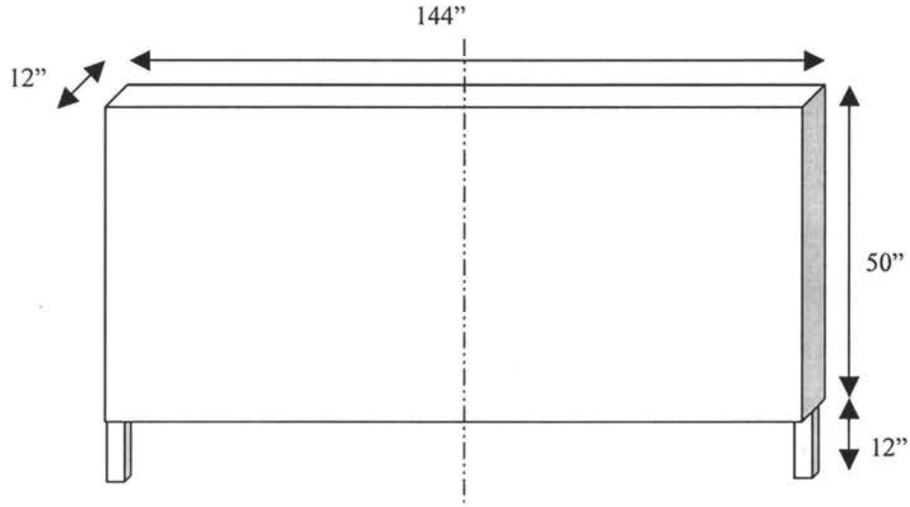


Fig. 1.1 Outline representation of a ground mounted signboard with posts

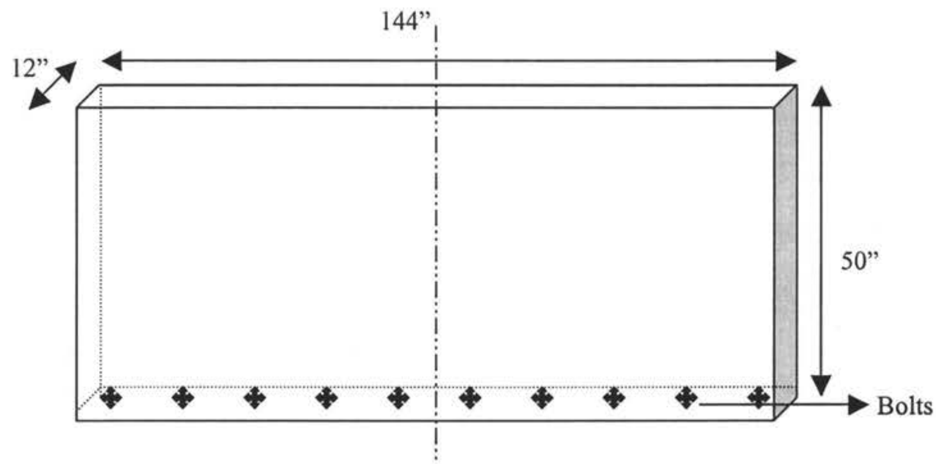


Fig. 1.2 Outline representation of a ground mounted signboard with bolts and anchors

The analyses of the results were performed on two types of signboard models:

- The reduced model, and
- The finite element model.

1.2 Reduced model

The cross-section of the frames was very complicated, as will be shown later. In order to obtain a general idea of how the stresses on the board were acting and to gain an overview of the behavior of the board for such high winds, reduced models of the boards were generated. A reduced model is a simple model of the board having a 'U' cross-section, which is similar to the outline of the original cross-section ignoring all the details of the model and having approximately the same dimensions as that of the original frame. The reduced model had equivalent mechanical properties such as cross-sectional area and moment of inertia as that of the original model. Hence, when loads are applied and analysis was carried out, the reduced model analysis gave approximately the same final results as that of the original one, giving good approximation of the behavior of the boards.

The main purpose of the reduced model is to obtain a measure of maximum values of stresses and deflection on the board. The following reduced models were generated in this project.

50"x144"dimension board:

- With posts
- With bolts and anchor

122"x98" dimension board:

- With posts
- With bolts and anchor

1.3 Finite element model

Once the results of the analysis on the reduced models were obtained, the finite element models for both the dimensions were generated using ANSYS software. The design on the actual models was carried out as per the detailed drawings provided by ASI Signs. The signboard was then divided into a number of elements. Main advantage of this element division is stresses and deflections on each and every element can be obtained and analyzed separately thereby giving very accurate results. As the study was carried out on each and every element, recommendations to the design can be made more specifically based on the results obtained. The finite element (FE) models were generated for both the dimensions of the board with posts.

Another proposal that was researched was the anchor and bolt design. This was attempted to make the manufacturers aware of the possibility of this type of mounting. As the results obtained from the reduced models indicated that in the bolt and anchor design, the maximum stresses were acting on the bolts and not on the frame, the analysis was not applied to the FE model. This is because the study of the behavior of stresses on bolts wouldn't vary whether it is a FE model or a reduced model, as the overall properties of the two models is same. The following FE models were generated in this project.

50"x144"dimension board:

- With posts

122"x98" dimension board:

- With posts

The design and analysis of both 50"x144" and 122"x98" dimensional signboards were carried out based on the following sequence of steps:

- Generation of computational model of airflow around the board using ANSYS CFD FLOTRAN software
- Generation of the reduced model
- Generation of the FE models
- Application of the pressures obtained from the CFD FLOTRAN analysis on both the reduced and FE models
- Analysis of the stresses and displacements obtained for both the models

Finite Element Analysis

Finite Element Analysis (FEA) is a computer-based numerical technique for obtaining approximate solutions to many of the problems encountered in engineering analysis[1]. In the finite element method, a structure is broken down into many small simple blocks or elements. The behavior of an individual element can be described with a relatively simple set of equations. Just as the set of elements would be joined together to build the whole structure, the equations describing the behavior of the individual elements are joined into an extremely large set of equations that represent the behavior of the whole structure.

In FE modeling, a complex region defining a continuum is condensed into simple geometric shapes called *elements*. The properties and the governing relationships are assumed over these elements and expressed mathematically in terms of unknown values at specific points in the elements called *nodes*. An assembly process, which involves maintaining the continuity of displacement, is used to link the individual elements maintaining the equilibrium. When the effects of loads and boundary conditions are considered, a set of linear or nonlinear algebraic equations is obtained. Solution of these equations gives the *approximate* behavior of the continuum or system. A greater degree of precision in the results can be achieved by increasing the number of elements.

ANSYS

The loads acting on the models can be of various types. They may be structural, thermal, fluid, electro-magnetic, or combinations of all these loads. ANSYS is computer based general-purpose design software, which can be used for a wide range of analytical computations. The ANSYS software is an excellent interface for carrying out FE analysis on any type of structure[2]. A computer is used to solve large set of simultaneous equations. Based on the solution, the behavior of the individual elements is extracted and consequently the stress and deflection of all the parts of the structure. The stresses are compared to the maximum allowable stresses of the materials used, to assess the strength of the structure.

CHAPTER 2

THEORY

The main aim of this project is to analyze the stresses acting on signboards at a wind speed of 100 *mph* that occur on the front panel of the board. The wind distribution on the front sheet was obtained through the CFD FLOTRAN analysis, which is discussed in detail later. To carryout the CFD analysis, it is important to determine the type of flow, which can be best achieved by calculating the Reynold's number. The control volume generation gives more accurate distribution of the wind speed around the board and thus allowing more accuracy in the analysis.

2.1 Calculation of Reynold's number

The Reynold's number *(Re)* gives a general idea of the type of the flow, whether it is laminar turbulent or transitional. The Reynold's number can be calculated using the following equation (2.1) to determine the flow type in this case[2].

$$Re = (\rho U b)/\mu \tag{2.1}$$

where,

Density of air (ρ) = 2.38E-3 $slugs/ft^3$

Velocity of air flow as suggested by ASI Signs (U) = 100 *mph*

Height of the board (b) = 62"

Viscosity of air (μ) = 3.74E-7 $lb\text{-}s/ft^2$

The Reynold's number using the above relation was obtained to be **4,822,544**, which determines the flow as turbulent.

2.2 Calculation of flow pressure around the signboard

The equivalent pressure (p) for a speed of 100 *mph* can be obtained from the following fluid flow equation (2.2).

$$p = 1/2\,(\rho\, U^2\, C_D) \tag{2.2}$$

where,

Coefficient of drag (C_D) = 1.145

Width of the frame (a) = 144"

Aspect ratio = a/b = 144/62 = 2.32

The corresponding value of C_D of 1.145 for a rectangular surface with an aspect ratio of 2.32 was obtained from the following graph[2], Fig. 2.2, which gives a relation between the coefficient of drag and the aspect ratio.

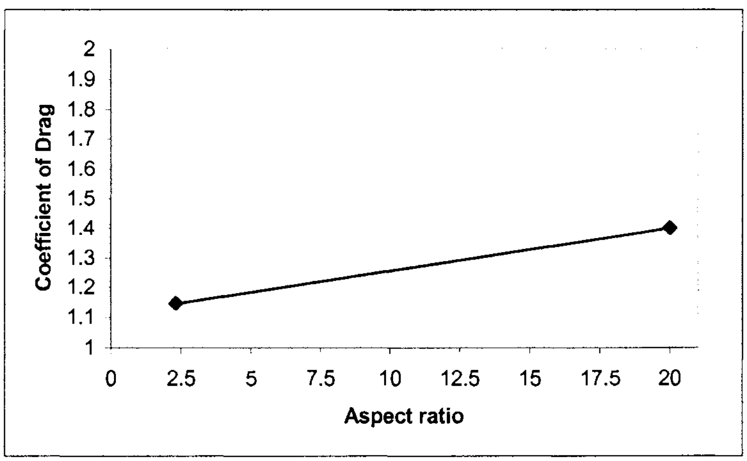


Fig: 2.2 Variation of Coefficient of Drag with Aspect Ratio

Using the above relation, the pressure acting on the board assuming a uniform wind speed of 100 *mph*, was observed to be **0.2035** ***psi***. This is the average pressure acting on the board.

2.3 Attributes considered for the analysis

The attributes that were considered to determine the safe limit of the design were the maximum tensile stress, maximum compressive stress, the von-Mises stress and the deflection in the frame and the panel.

von-Mises stress:

The failure of a material under stress can be predicted by comparing the stresses to the maximum limits, which are observed when the material is subjected to uni-axial loading. Some of the criteria include the maximum normal stress theory, the maximum shear stress theory and maximum von-Mises stress theory, which is also known as the maximum distortion energy criterion[3].

In the von-Mises stress criterion the failure is predicted when the sum of the squares of the differences of the principal stresses at a point attain the same level as they do at failure during a tensile test as shown in the following expression (2.3).

$$(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 2(\sigma_Y^2) \tag{2.3}$$

where, σ_1, σ_2, σ_3 are the principal stresses, and σ_Y is the material's yield stress from the tensile test.

The reason for using the von-Mises criterion as one of the attributes to predict the safety of the design of signboard is because for some ductile materials this criterion has been shown experimentally to predict failure better than the maximum shear stress criterion.

CHAPTER 3

EXPERIMENTAL WORK

The frame and the post of the signboard are made of aluminum and the front panel is made of fiberglass. To determine the material properties of the fiberglass, three tensile samples of thickness equivalent to 0.1875" were prepared and were subjected to tension test. From the results obtained through the mechanical testing of the three samples, the stress-strain curves were generated as represented in Fig. 3.1.

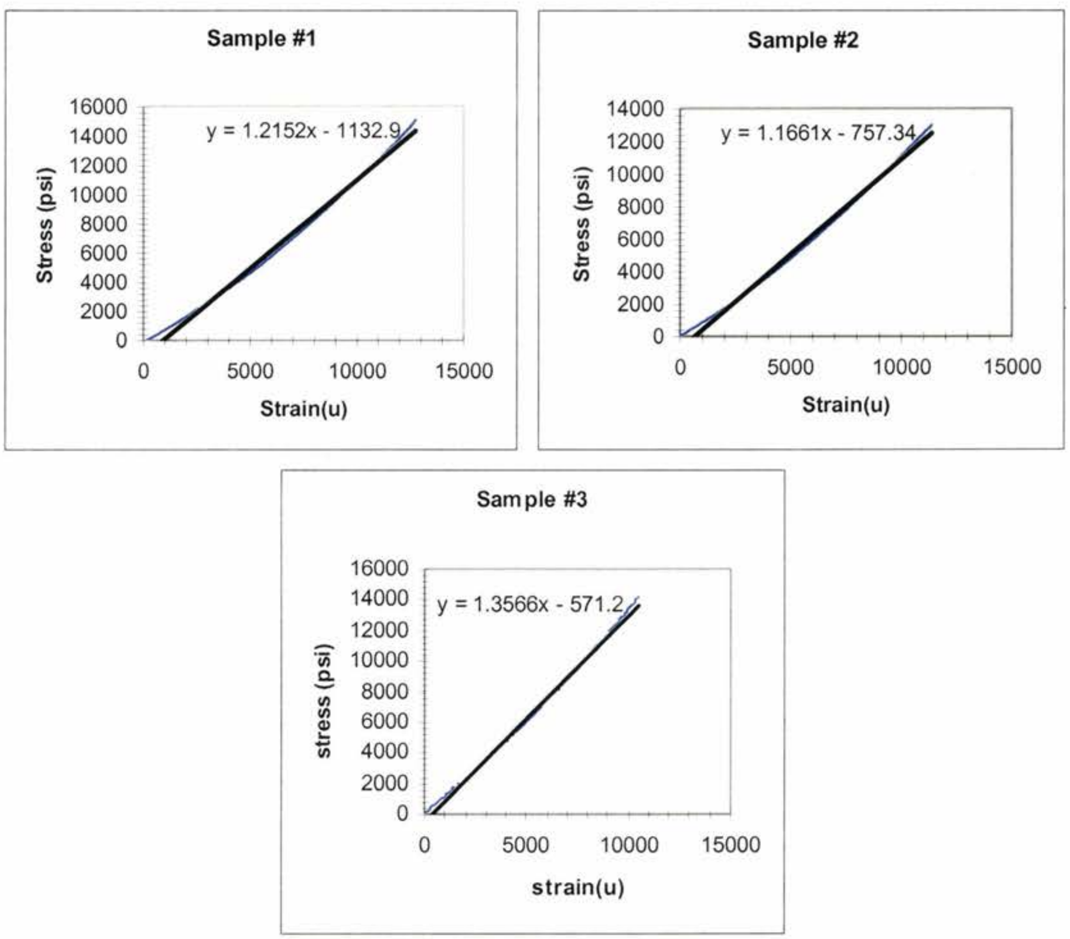


Fig: 3.1 Stress-Strain curves of the fiberglass samples

Table: 3.1 represents the summary of the material properties of fiberglass obtained from testing.

Table: 3.1 Summary of material properties of fiberglass

Sample #	Elastic Modulus (*ksi*)	Ultimate Strength (*psi*)
1	1032.1	13740
2	1155.6	14328
3	1356.6	12803
Avg.	**1181.4**	**13624**

The frame was made of aluminum (AL 6061-T6). The standard mechanical properties[4] of the AL 6061-T6 used in this work is shown in Table: 3.2.

Table: 3.2 Summary of material properties of aluminum AL

	Elastic Modulus (*ksi*)	Ultimate Strength (*psi*)
AL 6061-T6	10,000	45,000

CHAPTER 4

WIND DISTRIBUTION AROUND THE BOARDS

In reality, for a free flow of air, a wind speed of 100 *mph* on an open flat ground having no obstruction occurs at a height of 33 *ft.* as illustrated in Fig. 4.1.

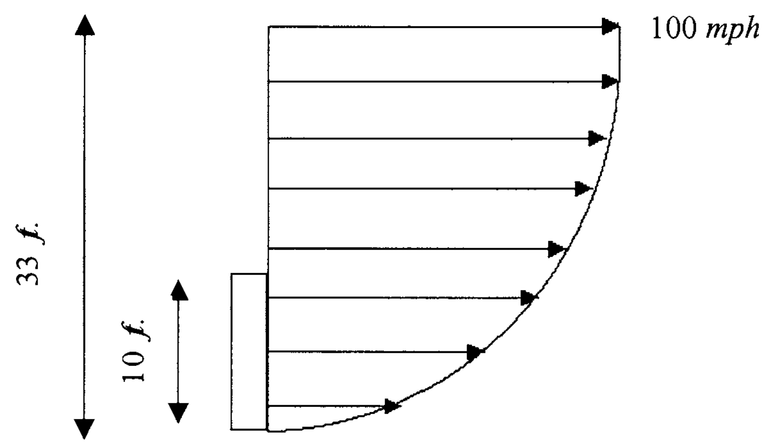


Fig. 4.1 Velocity profile on open flat ground for a wind speed of 100 *mph*

Based on the above velocity profile[5], although a wind speed of 100 *mph* will never occur at a 10 *ft.* mark, which is the height of the tallest model in this project, analysis was still carried out for a wind flow of 100 *mph* on both the boards to check the reliability of the design.

Control volumes for both the 50"x144" and 122"x98" models were generated so as to get an idea about the wind distribution around the boards. The control volume was generated such that it is 10 times the size of the board. Wind speeds of 100 *mph* were applied in the control volumes and were subjected to the pressure analysis. Since the boards were symmetric about one axis, the control volumes were generated for half the model of the boards. Generation of half the model saves a lot of time to carry on the analysis and also more elements can be generated in the model thereby resulting in more accurate results.

The front panel in fluid analysis was divided into 20x20 numbers of elements for ease in extracting the node pressures. The pressure distribution at each node of these elements were obtained through the control volume analysis and later applied to the fiberglass sheets of the reduced and the FE models for stress analysis.

4.1 ANSYS CFD FLOTRAN analysis

The CFD FLOTRAN option in ANSYS enables to analyze both two-dimensional and three-dimensional fluid flow fields[6]. Control volumes for both the dimensions of signboards were created using the CFD FLOTRAN software and were subjected to desired wind speeds. It was assumed that the direction of wind is perpendicular to the front panel sheet. Fig. 4.2 depicts the computational flow model of half the 50"x144" board and fluid flow around it.

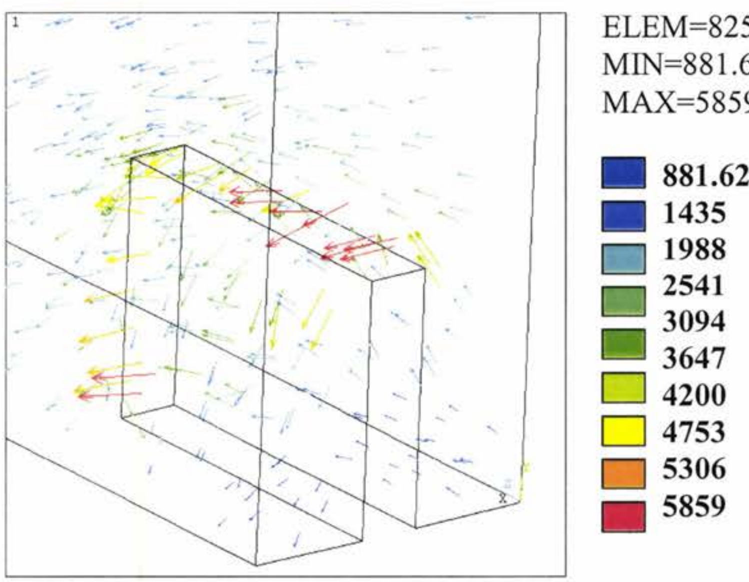


Fig. 4.2 Airspeed in in/sec around the 50"x144" sign board

The element type used to carryout the control volume analysis in ANSYS is FLUID 141[7]. This CFD model generation is used to study the pressure distribution around the board.

CHAPTER 5

REDUCED MODEL ANALYSIS

A reduced model was generated in this task to obtain an overall idea of the performance of the boards for high wind pressures. The reduced model had a simple 'U' cross-section for the frame similar to the outline of the actual frame ignoring all the minor details of the actual drawings given by ASI Signs. Fig.5.1 illustrates a clear comparison between the cross-sections of reduced and actual models.

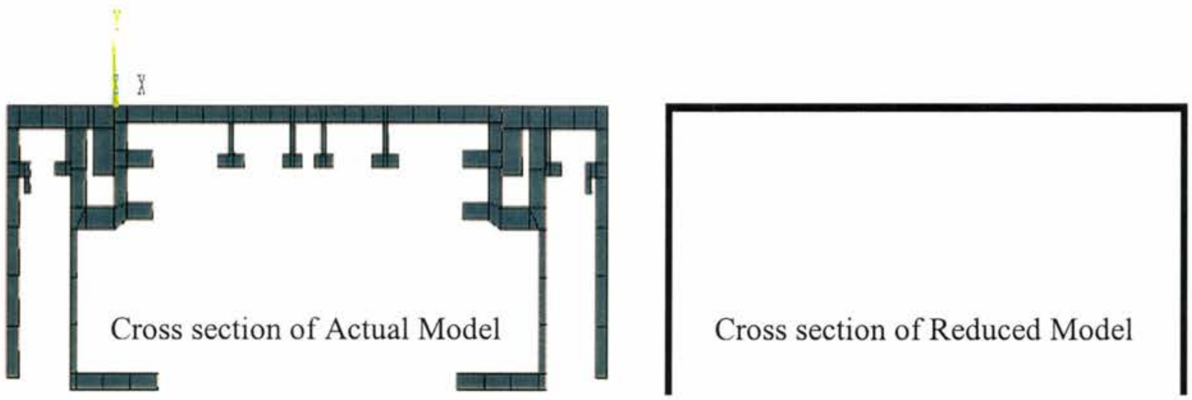


Fig. 5.1 Comparison of cross-sections of actual and reduced models

The reduced model gives a general comparison of the results of the original frame. The model was generated in ANSYS with nodes and elements and with approximately same outer dimensions as that of the original model. Appropriate material properties for the fiberglass panels and the aluminum frame were applied and it was ensured that the model had equivalent mechanical properties like the cross-section area and the moment of inertia as that of the original one.

The main purpose of a reduced model was to identify the maximum stresses point on the frame for 100 *mph*. After designing the frame, the pressure values obtained from the CFD FLOTRAN program were applied on the front fiberglass panel and the results were analyzed. The reliability of results was decided in comparison to the material's ultimate stress.

5.1 Analysis of 50"x144" model (with post)

The results obtained after the analysis for the 50"x144" frame can be summarized as follows.

Deflection:

The maximum deflection (DMX), as illustrated in Fig. 5.2, of the signboard was observed to be occurring on the surface of the front sheet where the load was directly applied. The displacement is of the order of 5.879".

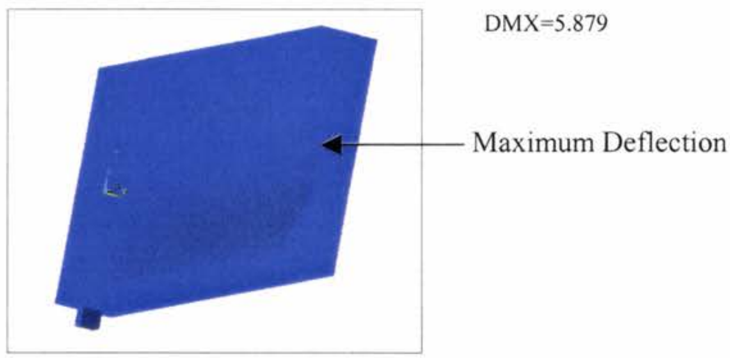


Fig. 5.2 Deflection of the panel of 50"x144" reduced model (with post)

The deflection of the frame alone as shown in Fig. 5.3, not considering the composite sheets is observed to be 0.577". The maximum deflection occurs at the center of the top-section of the frame. This value of deflection is just an approximation for the original model.

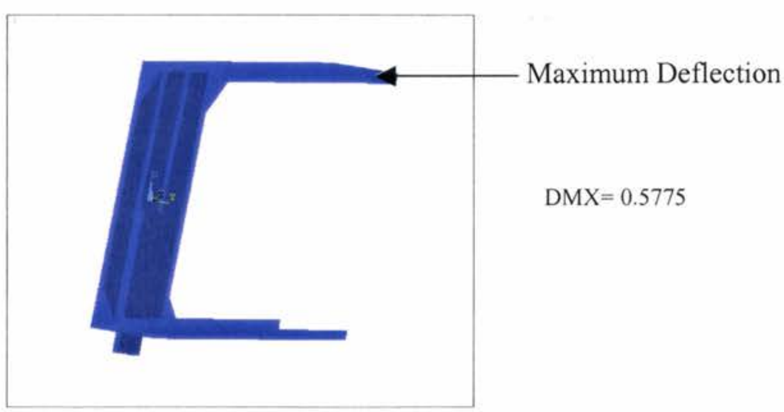


Fig. 5.3 Deflection of the frame of 50"x144" reduced model (with post)

von-Mises Stress:

The maximum value of von-Mises stress for the reduced model is found to be 51,632 *psi*, which still lies within the safe limit of the material. The point where the post enters the frame, as illustrated in Fig. 5.4 is observed to be having the maximum stress.

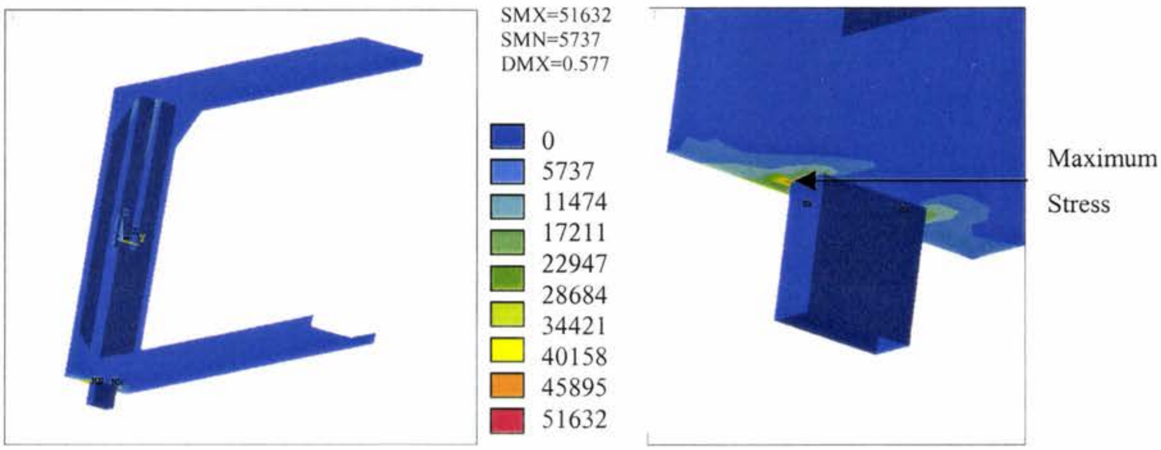


Fig. 5.4 Maximum von-Mises stress location in the frame of 50"x144" (with post)

Summary of the Results:

Maximum overall deflection with front panel = 5.98"

Maximum deflection with frame without the front panel = 0.58"

Maximum von-Mises stress observed = 51632 *psi*

Maximum shear stress observed = 3867 *psi*

Maximum Principal Stress in tension = 58217 *psi*

Maximum Principal Stress in compression = 57354 *psi*

5.2 Analysis of 50"x144" model (without post)

A reduced model of the signboard having a 'U' cross section was generated similar to the previous reduced model without the post support. This type of frame is mounted to the ground using bolts at various points in the bottom part of the frame. The analysis was carried out on half the model of the signboard, as it was symmetric about one axis. The model was anchored to the ground with bolts at five locations, each distanced at about 12". Fig. 5.5 represents the model of the frame and the bolt locations on it. Once the model is generated, appropriate boundary conditions are applied to the board as subjected to wind loads on the front panel and the analysis is carried out.

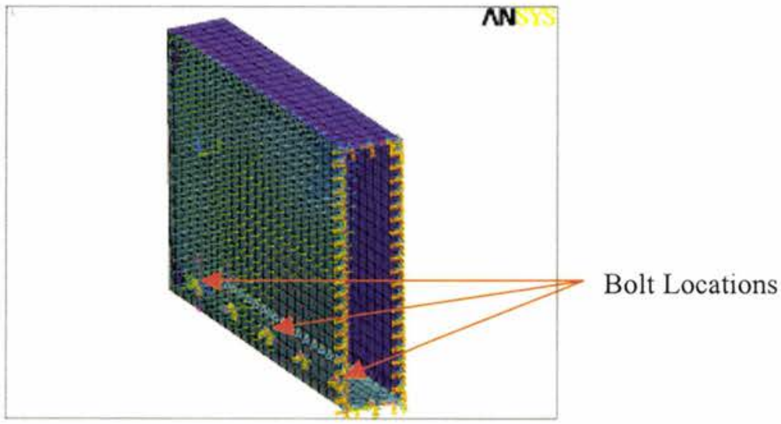


Fig. 5.5 Bolt locations and Boundary conditions of 50"x144" board (without post)

Deflection:

The deflection of the model including the frame is observed to be 6.847" (Fig. 5.5.1) and is observed in the side panels. Ignoring the panel deflection, the deflection of the frame is observed to be 0.2" (Fig. 5.6), which is observed to be occurring at the mid section of the top part of the frame.

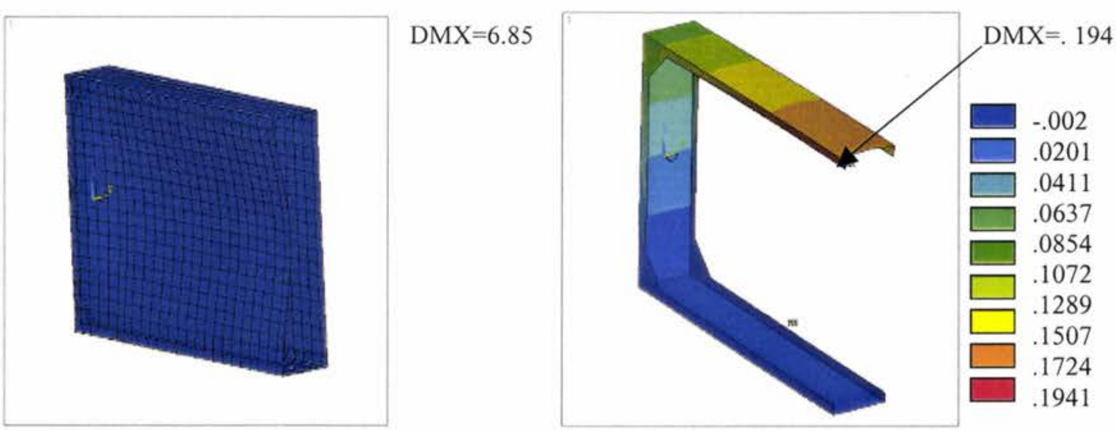


Fig. 5.6 Deflection of the 50"x144" reduced model (no post)

Tensile and Compressive Stresses:

The maximum tensile stress on the frame is observed to be 9342 *psi* occurred at the bottom edge of the frame (Fig.5.7). This value of tensile stress lies within the safe limit when compared to the ultimate stress with a factor of safety of 4.8.

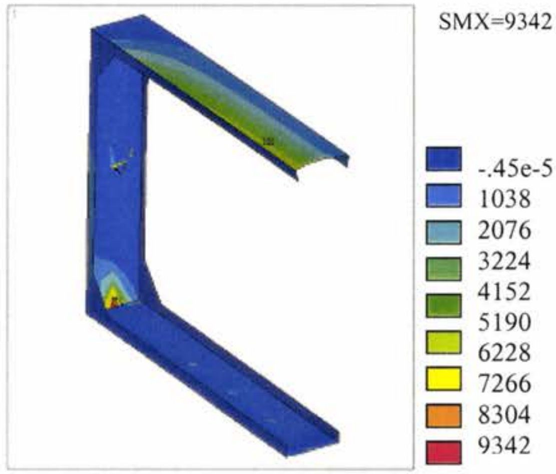


Fig. 5.7 Tensile Stress distribution on 50"x144" reduced model (no post)

The maximum compressive stress was obtained to be 8058 *psi* with a factor of safety of 6.0 in comparison to the ultimate stress value. Highest value of compressive stress occurred at center on the top section of the frame (Fig. 5.8).

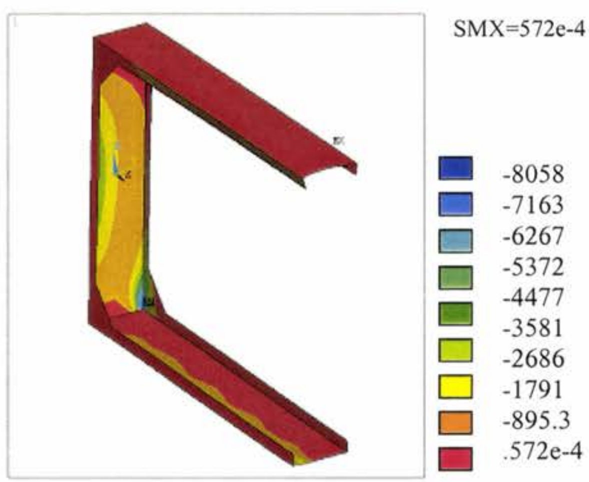


Fig. 5.8 Compressive Stress distribution on 50"x144" reduced model (no post)

Shear Stress:

The shear stresses in XY, YZ and XZ directions are observed to be 810.74 *psi*, 1183 *psi* and 2190 *psi*, respectively. Again, these values of shear stresses are very small when compared to the maximum allowable shear stress for the material. The board is stressed maximum in shear in the YZ direction. The bottom edge of the frame is stresses highest in all the planes. Fig. 5.9 indicates the shear stress distribution in all the three planes.

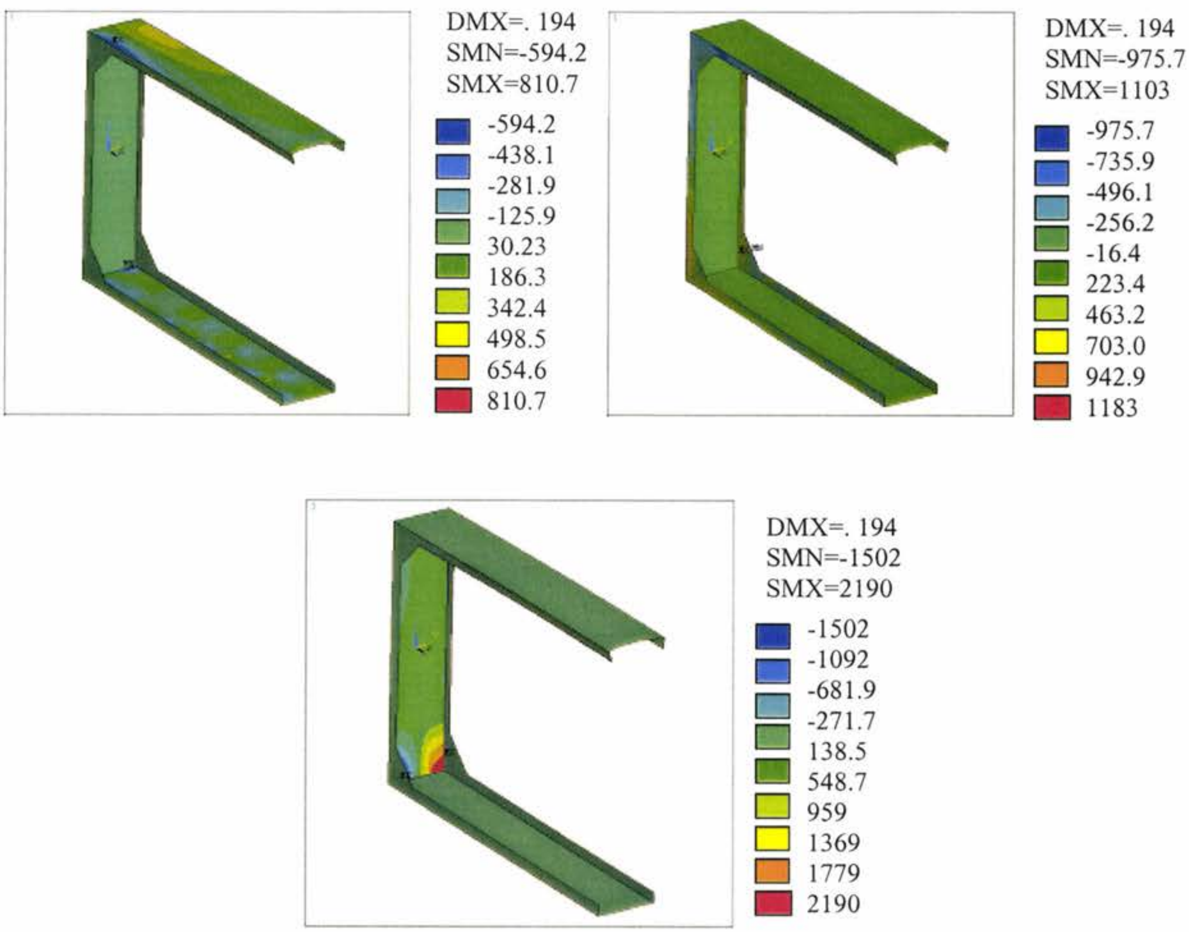


Fig. 5.9 Shear stress in XZ, YZ and XZ directions in 50"x144" reduced model (no post)

von-Mises Stress:

The von-Mises stress on the frame is observed to be 8606 *psi* with frame alone (Fig.5.10.1) and 10638 *psi* with the panel included (Fig. 5.10.2). The maximum value of stress on the frame is observed to be occurring at the left most corner of the model.

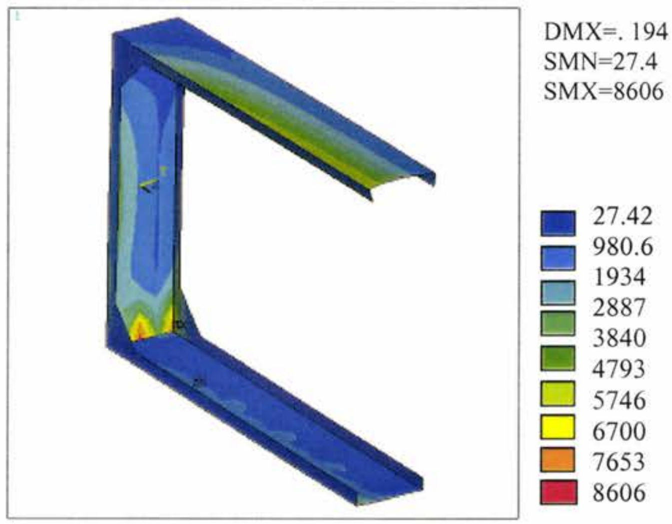


Fig. 5.10.1 von-Mises Stress distribution on the frame of 50"x144" reduced model (no post)

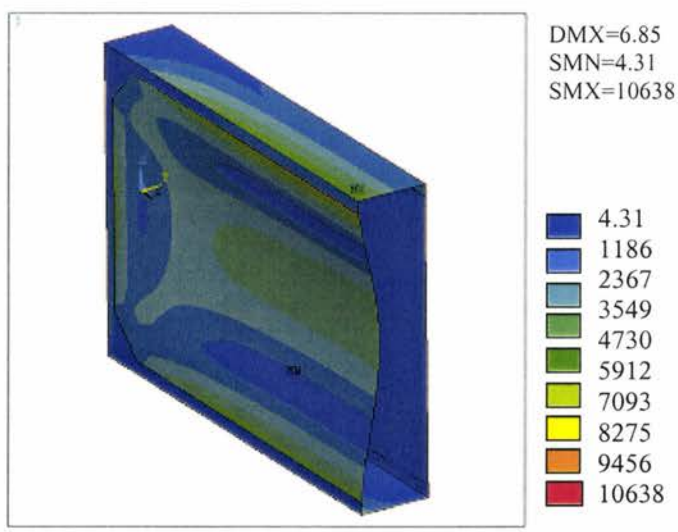


Fig. 5.10.2 von-Mises Stress distribution on the entire board 50"x144" (no post)

Summary of Results for bolt:

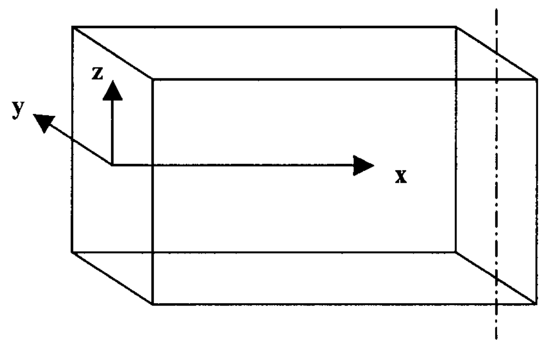
The maximum values of forces and moments on the extreme left bolt, which is observed to be carrying highest value of forces when compared to all the other bolts, are summarized as follows. The coordinate directions of the bolts are the same as for the frame.

Maximum Forces:

$F_x = 90.3$ *lb*

$F_y = 910.9$ *lb*

$F_z = 6632.0$ *lb*



Maximum Moments:

$M_x = 99.7$ *lb-in*

$M_y = 67.2$ *lb-in*

$M_z = 1.3$ *lb-in*

For the design of the anchor bolts the following values will be more appropriate. These values of stresses do not include the factors of safety.

Maximum Tensile load = 6632 *lb.*

Maximum Shear load=916 *lb*

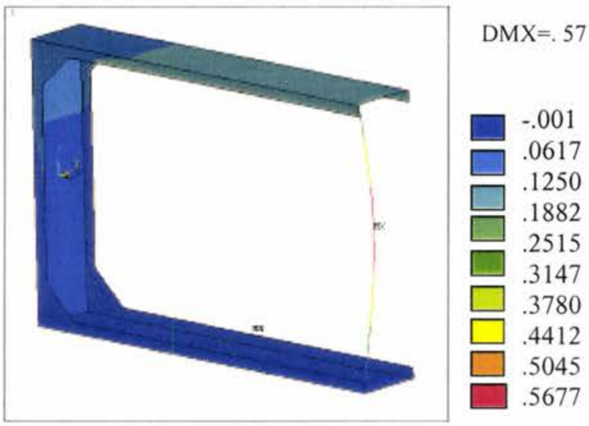
Maximum Bending Moment=120.2 *lb-in*

Maximum Twisting Moment=1.3 *lb-in*

5.3 Analysis of 50"x144" model (without post-with central support)

An additional analysis on the 50"x144" dimensional signboard was carried on the reduced model with a central support to the frame so as to reduce the stresses and deflection on the panel of the board.

This analysis resulted in reduction of the deflection of the front panel of the signboard as indicated in Fig. 5.11. Maximum deflection of the central support is of the order of 0.57" and occurred at the middle and that of the frame is observed to be 5.716". The von-Mises stress of 26559 *psi* (Fig. 5.12) is observed to be occurring in the middle of the bottom part of the frame where the support joins with the frame. This value has a factor of safety of 5.6, which is very safe.



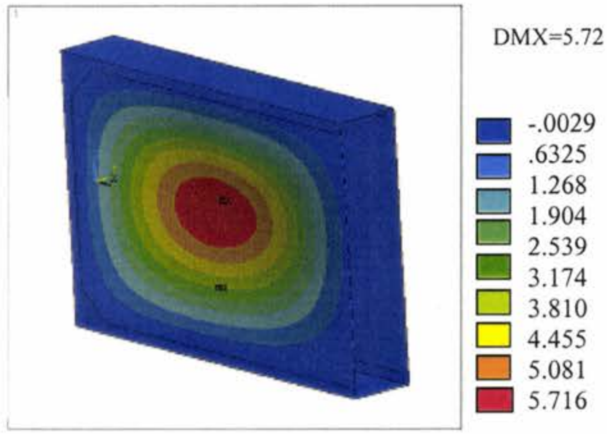


Fig. 5.11 Deflection of the 50"x144" signboard without posts with central support

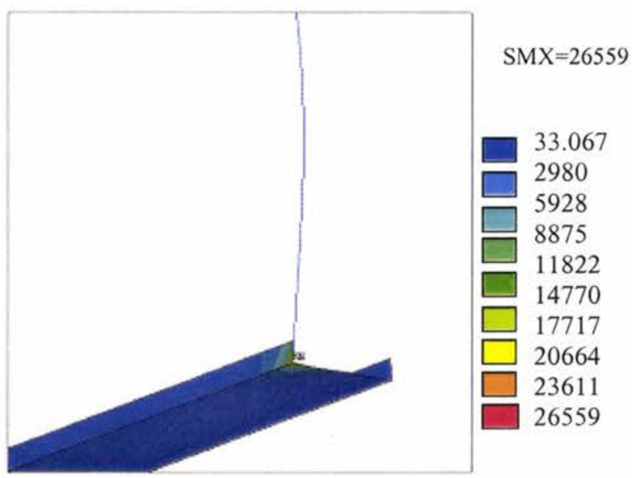


Fig. 5.12 von-Mises stress in the 50"x144" signboard without posts with central support

Summary of results for Frame:

Without central support:

Maximum displacement in the panel = 6.847”

Maximum displacement of the frame = 0.2”

Maximum von-Mises stress = 8606 *psi*

Maximum principal tensile stress = 9342 *psi*

Maximum principal compressive stress = 8058 *psi*

Maximum shear stress = 1183 *psi*

With central support:

Maximum displacement in the panel = 5.716”

Maximum displacement of the central support = 0.567”

Maximum von-Mises stress = 26559 *psi*

5.4 Analysis of 122”x98” model (without post)

A reduced model of the signboard for the 122”x98” model was generated similar to the other reduced models having a ‘U’ cross with equivalent mechanical properties as that of the original model. In the case of this tall model, three bolts were used and were anchored to the ground at the centerline of the bottom part each distanced at 14”. The loads and appropriate boundary conditions were then applied onto the model to analyze the results.

Deflection:

The deflection of the frame was observed to be 88.649”, on the composite front panel. The deflection of 12.141” in the frame was observed to be occurring at the top part of the frame. This is represented in Fig. 5.13. This high value of deflection is because the analysis was carried out without a base support. Adding a steel plate to the interior of the base can reduce this high value of deflection. Even the panel is observed to be having very high value of deflection but a simple theoretical analysis can prove a reason for this value to be high for this thickness of the fiberglass panel.

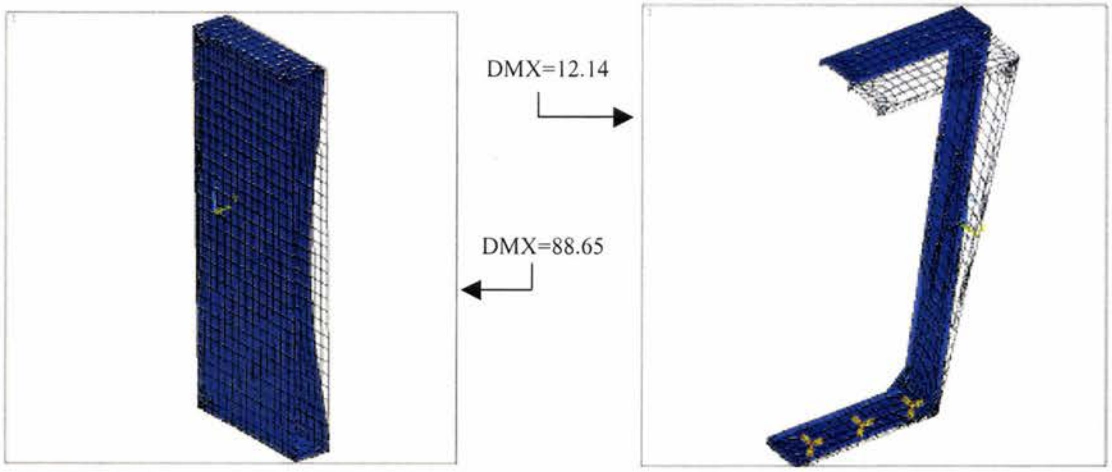


Fig. 5.13 Deflection of the 122"x98" reduced model (without posts)

Stresses:

The maximum value of stress on the frame is observed to be occurring at extreme left bolt and is of the order of 222,654 *psi* as indicated in Fig. 5.14. This high value of stress also can be minimized when a steel plate is added to the interior of the base.

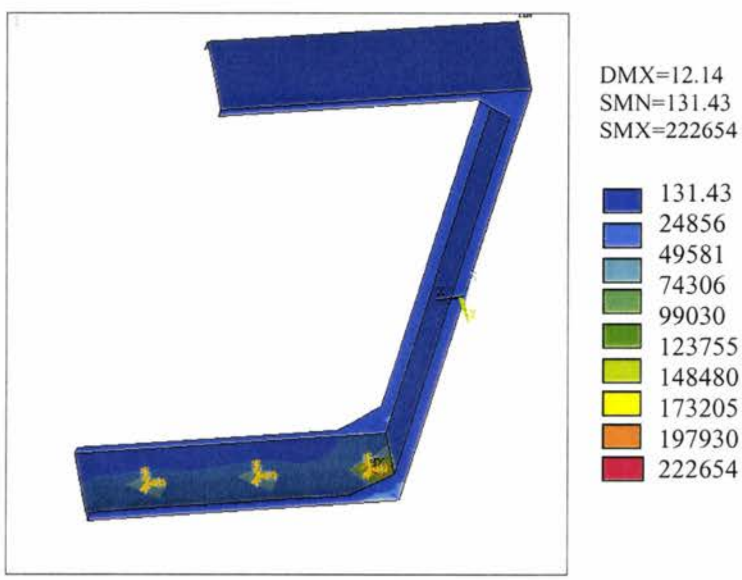


Fig. 5.14 von-Mises stresses for reduced 122"x98" signboard (no post)

Summary of results for bolt:

The maximum values of forces and moments on the extreme left bolt, which is observed to be carrying highest value of forces when compared to all the other bolts, are summarized as follows.

Maximum Forces:

F_x = 1223.9 *lb*

F_y = 2394.9 *lb*

F_z = 10550 *lb*

Maximum Moments

M_x = 9005 *lb-in*

M_y = 757.5 *lb-in*

M_z = 3.76 *lb-in*

Based on the above listed values of forces the values of tensile, shear and bending moment for the anchor bolts can be obtained as follows.

Total tensile force = 10550 *lb*

Total Shear load = 2690 *lb*

Maximum bending moment = 9038 in-*lb*

Summary of results for frame:

Maximum displacement in the panel = 88.649"

Maximum displacement of the central support = 12.141"

Maximum von-Mises stress = 222654 *psi*

CHAPTER 6

DESIGN OF FRAME WITH ACTUAL CROSS-SECTION

The model with actual cross-section as provided by ASI Signs was carried on in finite element analysis software called ANSYS. The following are the procedural steps followed in generating the actual cross-section of the signboard as specified in the ASI standards.

Step 1 – Building the model: The basic structure of the signboard was built using the various design tools according to the specifications that were provided.

Step 2 – Assembling the model: The signboard model was simplified into three different parts and was finally assembled for the final structure.

Step 3 – Applying loads and boundary conditions: The loads and the boundary conditions were applied on the signboards based on the calculations that were obtained from the control volume analysis.

Step 4 – Solving the problem: The model was then finally subjected to stress analysis.

6.1 Building the model

The basic structure of the signboard was modeled as per the design specifications provided by the ASI signs.

The model of the frame of the signboard was generated in a sequential order since the cross-section of the model is complicated. The model was generated with nodes and elements. Prior to this, the model was generated using key points and lines and was then subjected to free mesh generation. Automatic generation of the elements has created so many numbers of elements such that the degrees of freedom were outside the range of available software. Hence, the cross-section of the frame was modeled first using nodes and elements. For ease and consistency in modeling the elements, the shape of each element was initially specifies and was generated. The following figure (Fig. 6.1) gives an idea as how the cross-section was divided into elements. Later, a program was generated using ANSYS code to extrude the elements in the Y direction. Care was taken while programming such that the extruded elements and the nodes followed a concurrent order and had the elements of regular shape.

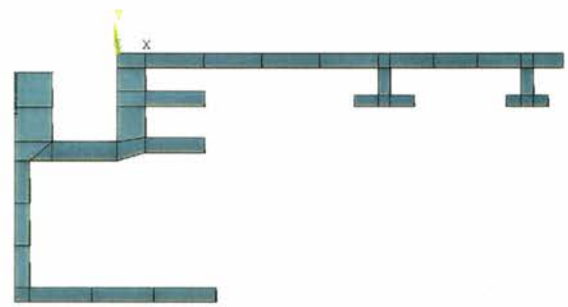


Fig. 6.1 Representation of division of area into elements

Programming

A program was developed using ANSYS to generate the nodes and elements of the signboard in a sequential order. For ease in generating the model and to develop the program, the model was divided into five parts: top part, side part, bottom part, the post and the front panel. Individual programs were written using the ANSYS programming software for all the parts to fill out the nodes and elements in a definite order. Later all these programs were read into a single ANSYS database after taking care of the rotation angles and joining points of each of the model to the other. Once all the parts are in one screen, the adjoining nodes of the parts were coupled using the ANSYS 'couple-node' option so as to form a single model.

The signboard has one axis of symmetry. Hence, only half of the frame was modeled to simplify the design. The process of modeling was done in three parts in three different files. The following procedural steps give a basic idea about the various steps involved at the design level.

- Create Nodes
- Generate Elements
- Extrude elements
- Reflect the top part
- Model the post of the sign-board

- Modeling the Frame
- Assemble parts
- Join the parts

Create Nodes:

As a first step the cross-section of the frame was developed using the ANSYS software. According to the dimensions and the geometry of the frame, convenient node points were chosen as represented in the illustration.

Generate Elements:

In the process of generating the elements, certain assumptions were made. All the curved parts in the cross-section were considered to be straight-edged. Also, the angular cuttings in the frame were taken straight, as they won't contribute much to the stress analysis (Fig.6.2.1).

Fig. 6.2.1 Curved and Ridge ends taken as straight edge

Later, all the node points were joined by the elements. In this case the element type used was a SOLID45. Since the design of the frame is a three-dimensional model, a SOLID 45 is used, since it is the element type used for three-dimensional modeling of the structures. Eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions define this element type. To generate an element, the nodes were selected in a sequence to get a uniform shape of the elements throughout the structure. Fig. 6.2.2 and Fig. 6.2.3 represent the cross-sections of the top part of the frame and side part of the frame, respectively.

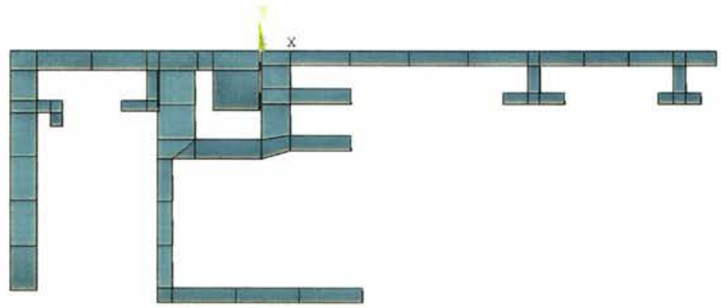


Fig. 6.2.2 Cross section of top part of the frame

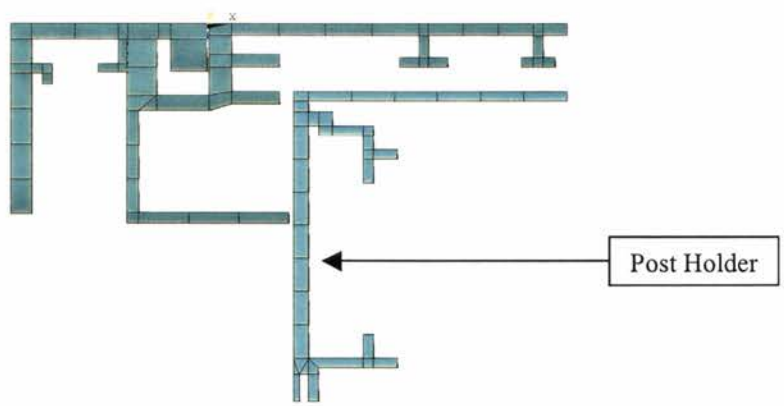


Fig. 6.2.3 Cross-section of side part of the frame and post holder

Extrude Elements:

Once the cross-sectional nodes are joined by the elements; the cross-sections of the top and the side parts of the frame were extruded in the third direction to obtain the three dimensional structure of the frame. Initially a code was developed to divide the extruded part into a specific number of elements to ensure the total number of elements in the entire model does not exceed the maximum limit, which ANSYS can handle. Henceforth, the elements in the extruded part were obtained in a specific order where uniform number of elements was obtained throughout the cross-section along the extrusion. Fig. 6.3.1 illustrates the extrusion of top part. The same pattern was carried out for the side part of the frame (Fig. 6.3.2)

Fig. 6.3.1 Top section of the frame after extrusion

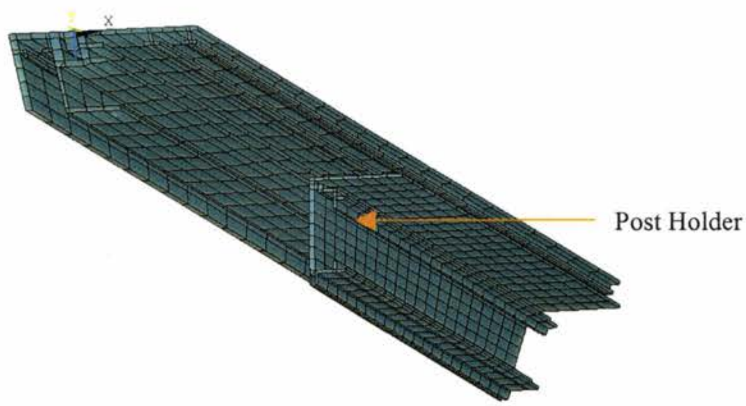


Fig. 6.3.2 Side section of the frame after extrusion

Reflect the top part:

The bottom section of the frame is just the reflected image of the top section. The top part, as per the axial conditions in this case, was reflected about X-axis. To get a correct reflection of the image the origin is shifted to a corner point in the top part of the frame and the new origin acted as the center of reflection. Once the origin is shifted the part is reflected about that point in an appropriate plane to get the exact reflection of the image.

Model the post of Signboard:

The post of the signboard is a hollow rectangular structure with a thickness of 0.1", which fixes itself into the post holder and extends beyond the lower end of the frame so as to be encased into the ground when mounted. The outer dimension of the cross section of the post is of the order of 4.062" x 2.094" (Fig. 6.4). In this case the post is initially designed as a volume starting from the post holder. Once the volume is obtained as per the required dimensions, it is set to free mesh generation to get the nodes and elements. The mesh tool option in ANSYS enables to pre-define the number of divisions desired in a solid part instead of having a free mesh. The free mesh tool generates elements according to the given precision and the shape of the structure. In order to get a uniform mesh along the entire structure, the lines were evenly so that the mesh does not concentrate at one point.

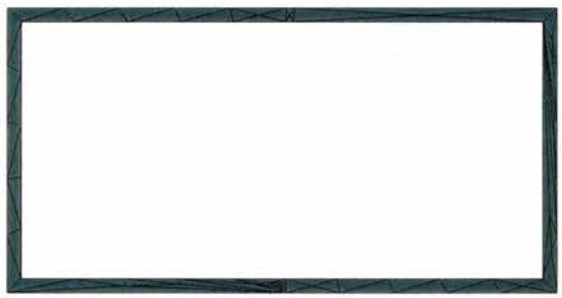


Fig. 6.4 Cross-section of the post

Modeling the frame:

Once the full model of the frame is obtained the front and back sheets are attached to the frame. These sheets in the actual signboard are made of composite materials. The element type used for the analysis of the sheet was a SHELL63. This element type has both bending and membrane capabilities. It has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x-, y-, and z-axes. The frame was modeled using nodes and elements. The nodes were generated initially and were attached using elements. The numbering of these elements in a sequential order will simplify the application of the loads on the sheet.

6.2 Assembling the model

All the three parts of the frame- the top, the bottom and the side parts, after modeling were assembled to get the final structure of the frame. For doing this, all the three parts of the design were saved as log files and then were read into a single file one after the other so as to get the final structure of the frame. Once the final structure of the frame was obtained, the front panel of the board made of composite material is also read as a log file into the same database file taking care of the starting point (origin) of the work-plane. Fig. 6.5.1 represents the full model of the frame and Fig. 6.5.2 represents the entire model of the signboard with the front composite sheet panel. Care was taken in the program so that the node and the element numbers were automatically read and their continuity maintained. The programming capability was fully used for this. Various text files, which were used to generate the models, are attached in the appendix.

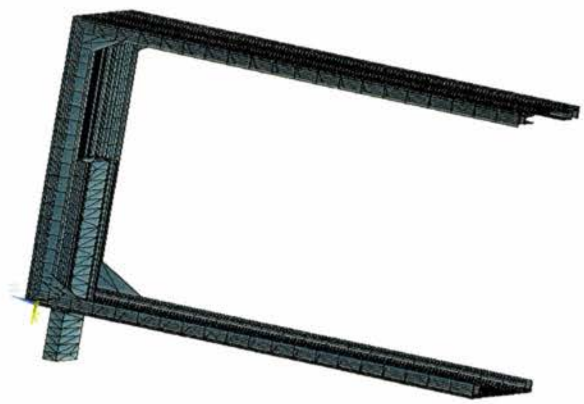


Fig. 6.5.1 Assembled model of the frame of 50"x144" board

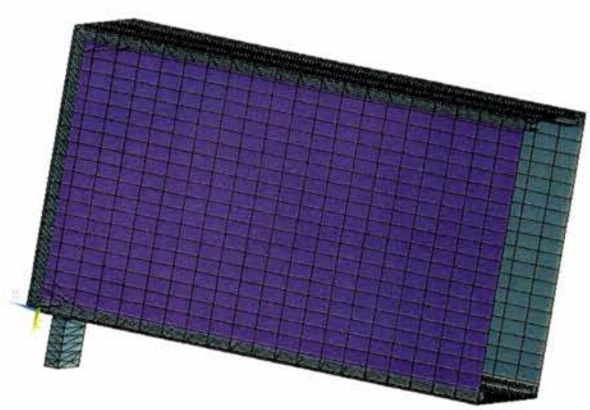


Fig. 6.5.2 Assembled model of the frame with front panel of 50"x144" board

Joining the parts:

All the three parts of the frame after being collected in one single file were joined to each other. The process of coupling attaches the nodes to form a fixed joint (Fig. 6.6). This process therefore ensures that all the three parts of the frame after the assembly are perfectly glued to each other to form a single structure. Hence, when the nodes were generated in each part, the adjacent line or surfaces of various parts had exactly same number of nodes. This helped in coupling of coincident nodes.

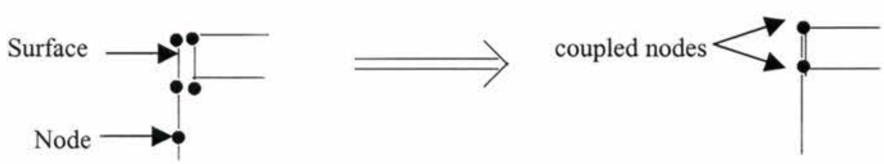


Fig 6.6: Process of coupling nodes

The coincident nodes were coupled in all the degrees of freedom, for both rotation and translation. Where there are no coincident nodes, the joining of the parts was done by coupling the nearest nodes on the end surfaces of each part in all degrees of freedom to make certain that it is as good as gluing the nodes to form a common node for both the parts. The common nodes and nearest nodes of all the parts were coupled therefore forming a continuous structure. The node coupling is as shown in Fig 6.7. Coupling is shown as asterisk in green color.

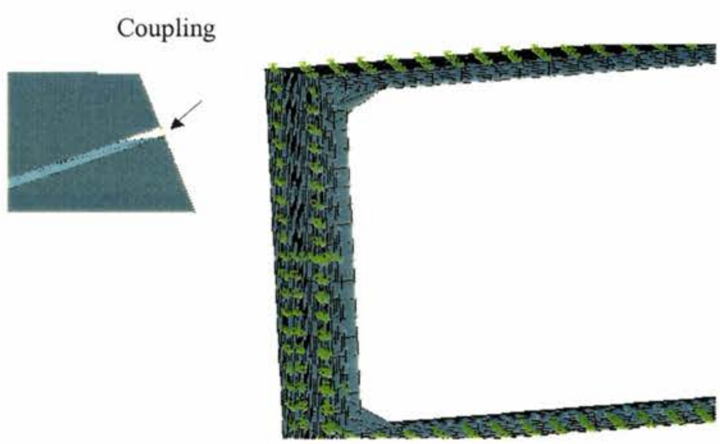


Fig. 6.7 Coupling of coincident nodes

Once the entire sheet is designed, the nearest nodes on it are coupled with those of the frame so that the sheet also would be a part of the frame. The joining of the sheet to the frame was tried in a couple of ways. Initially a contact pair was developed between the frame and the sheet. A contact element is a pseudo-element, which acts as a common surface to either of the parts. It just acts as a common surface for uni-directional load. If the load is applied from the opposite direction it doesn't work as a common element. But this didn't turn out to be fruitful for this analysis. The contact elements were difficult to get a converged solution. Hence another approach was used to get the solution. The nodes of the frame were coupled to those of the sheet.

122"x98" Dimension Signboard

The same modeling procedure was carried out on for the 122"x98" dimensional signboard.

CHAPTER 7

ANALSYIS OF ACTUAL MODELS

The main aim of this project is to check the adequacy of the model in high wind pressures. The maximum wind pressure for which the frame was designed was 100 *mph*. Earlier the analysis was carried out on a reduced model to obtain the loads acting on the frame. The reduced model was generated for both the dimensions of the frame such that they have equivalent cross-sectional area and same moment of inertia as those of the actual models.

7.1 Analysis of 50"x144" actual model

The frame, after being modeled, is subjected to wind pressure of 100 *mph*. The pressure values applied on the nodes of front panel are obtained from the CFD analysis.

Deflection:

The maximum deflection of the signboard with the composite sheet taken into consideration is observed to be 5.155", which is reasonably safe. Since, the main focus of the investigation was the frame design, the deflection and the stresses in the frame were studied carefully. The deflection of the frame was observed to be 0.998", as shown in Fig. 7.1.

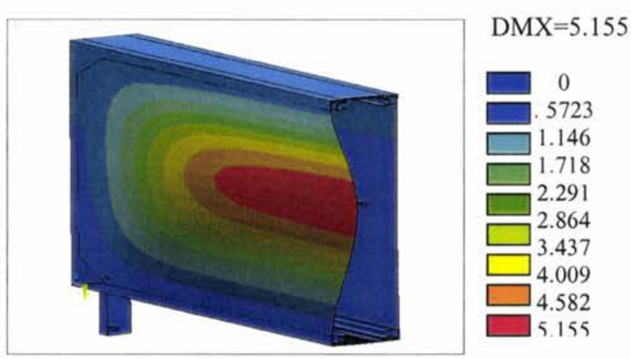


Fig. 7.1 Deflection of 50"x144" signboard with front panel

The maximum deflection on the frame is observed to be 1". This maximum deflection is observed at the top part in the middle of the frame. Fig. 7.2 represents the deflection pattern in the frame.

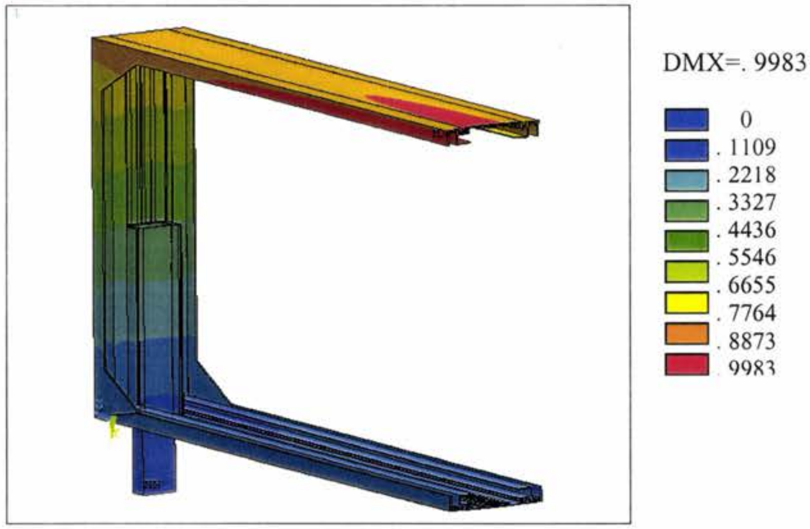


Fig. 7.2 Deflection of the frame of 50"x144" actual model

The rotation of the frame due to the wind pressure is observed to be 0.083 degrees, Fig. 7.3. This maximum rotation of the frame is observed at the center of the top section. This is a very small amount of rotation and would not be a cause of failure.

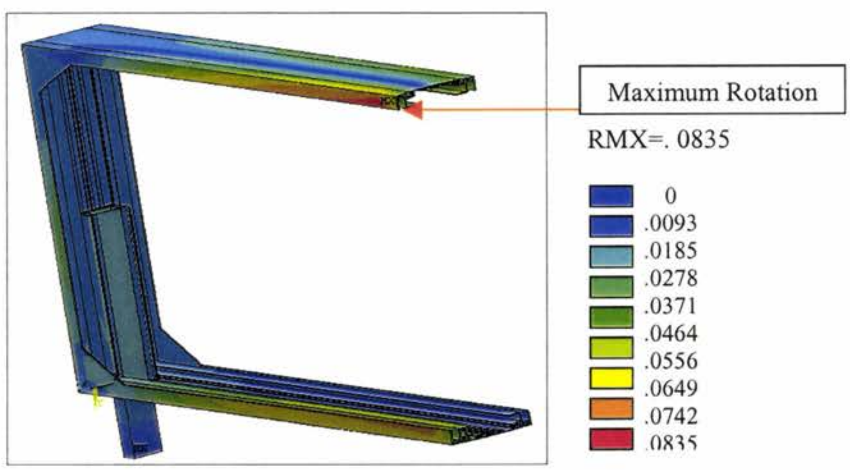


Fig. 7.3 Deflection of the frame of 50"x144" actual model

Tensile and compressive stresses:

The maximum tensile stress on the frame is 35,694 *psi*. This maximum value of the tensile stress is observed to be occurring on the post (Fig. 7.4), which is being mounted in the ground. The maximum value of the stress in compression is obtained as 14,637 *psi*. This maximum value of the compression as shown in Fig. 7.5 also occurred on the post but on the opposite side as that of the maximum tensile stress point.

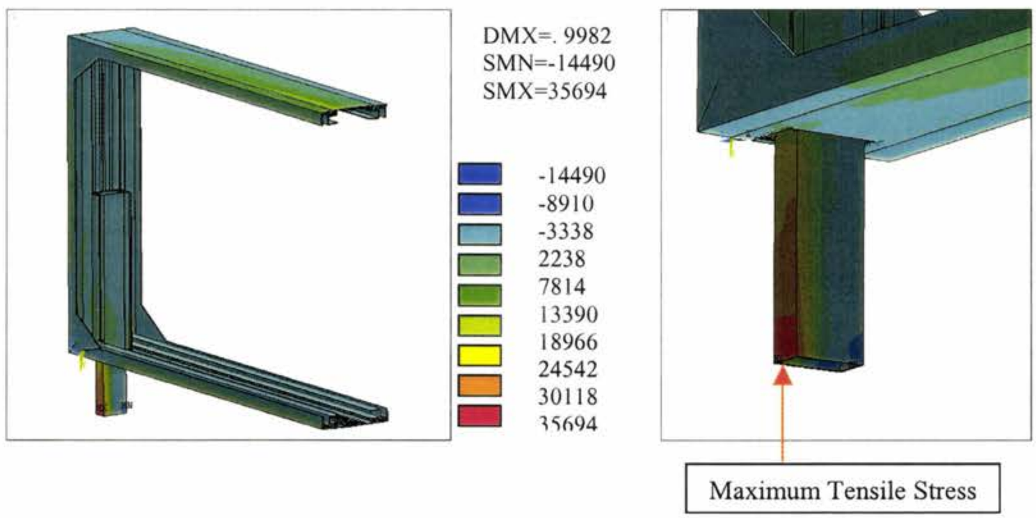


Fig. 7.4 Tensile stress distribution in 50"x144" actual model

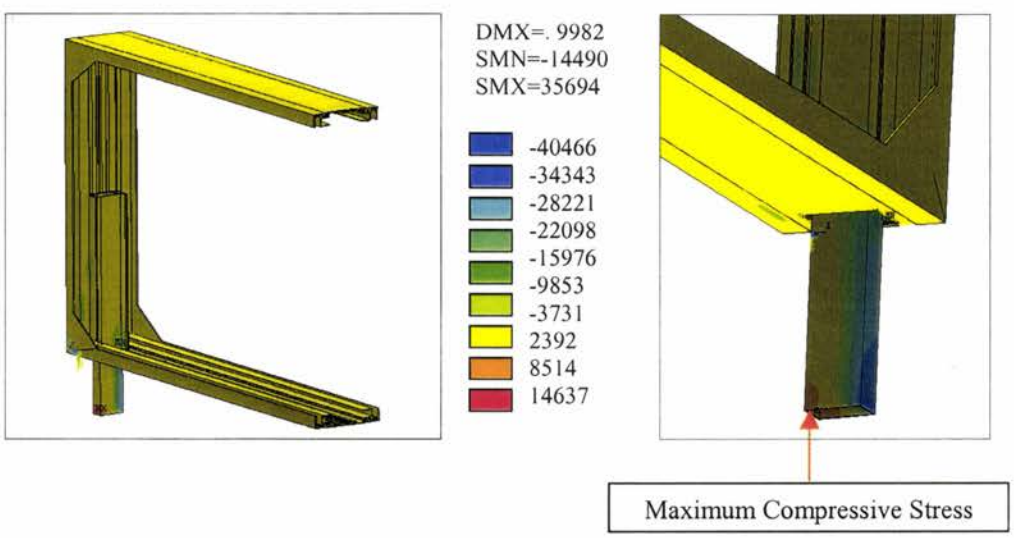


Fig. 7.5 Compressive stress distribution in 50"x144" actual model

Shear stress:

The shear stresses in the frame lie in the safe limit. The maximum shear stress in the frame is observed to be 16,955 *psi* in the YZ-Plane. The Fig. 7.6 represents shear stress in all the three planes.

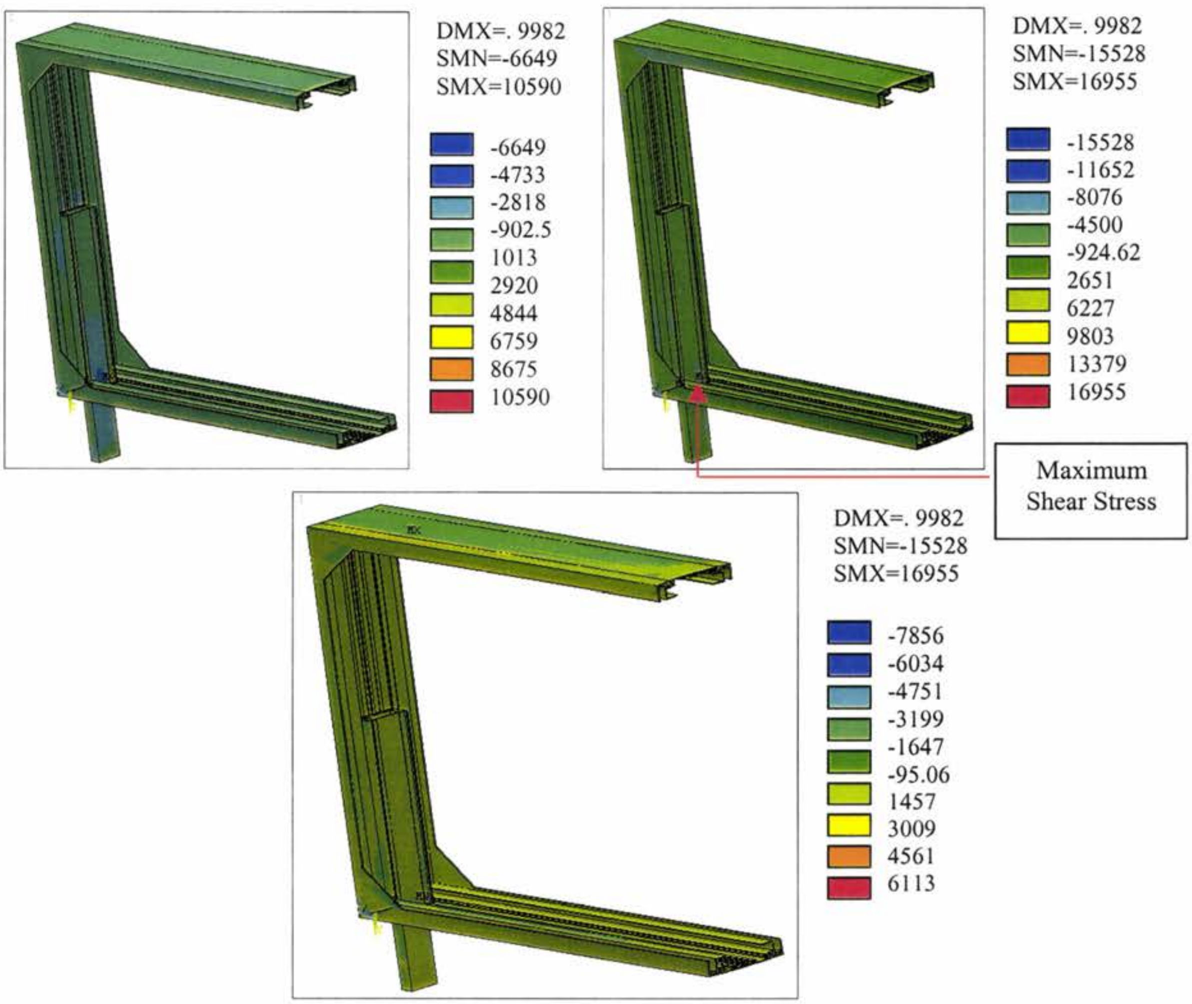


Fig. 7.6 Shear Stress- XY, YZ and XZ planes of 50"x144" actual model

von-Mises stress:

The maximum value for the von-Mises stress is observed to be 34,262 *psi*. This is also observed at the junction of the post and the frame as indicated in Fig. 7.7. This high value of stress can be reduced considerably by attaching a central support in the frame.

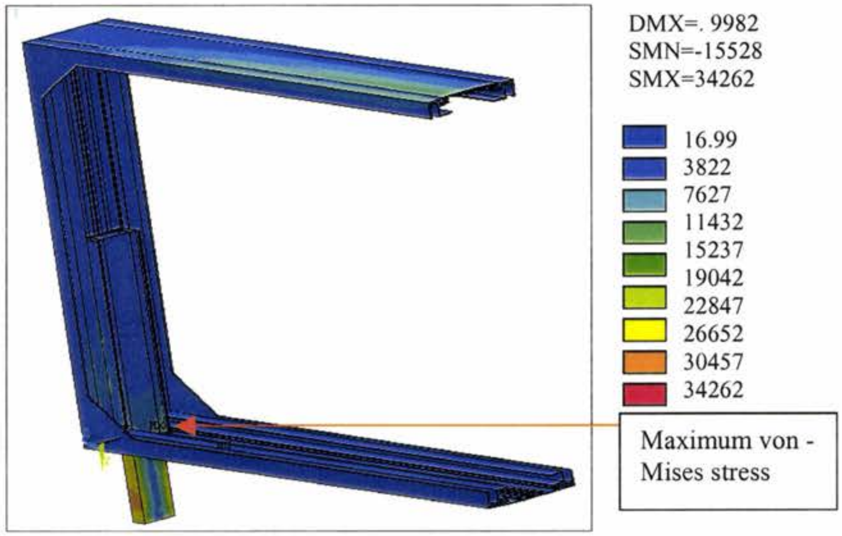


Fig. 7.7 von-Mises stress of 50"x144" actual model

Summary of the Results for 50"x144" Signboard:

The maximum values of displacements and stresses can be summarized as follows.

Maximum displacement in the panel = 5.155"

Maximum displacement of the frame = 0.998"

Maximum von-Mises stress = 34262 *psi*

Maximum principal tensile stress = 35694 *psi*

Maximum principal compressive stress = 14637 *psi*

Maximum shear stress = 16955 *psi*

7.2 Analysis of 122"x98" actual model

The analysis of the 122"x98" signboard was carried out the same way as that of the other models. Once the signboard is designed, it is subjected to a wind pressure of 100 *mph*.

Deflection:

The maximum deflection of the signboard with the composite sheet taken into consideration is observed to be 56.113", which is very high. The high value of displacement will be analyzed in the following chapters. This is represented in Fig. 7.8. This has to be taken care of as it might cause some damage to the lighting circuits. As the main aim of the project is to model the frame for safe stresses, the deflection and the stresses in the frame are taken care of while ignoring the sheet. The maximum deflection on the frame is observed to be 4.173" occurring at the middle of the top part of the frame (Fig. 7.8).

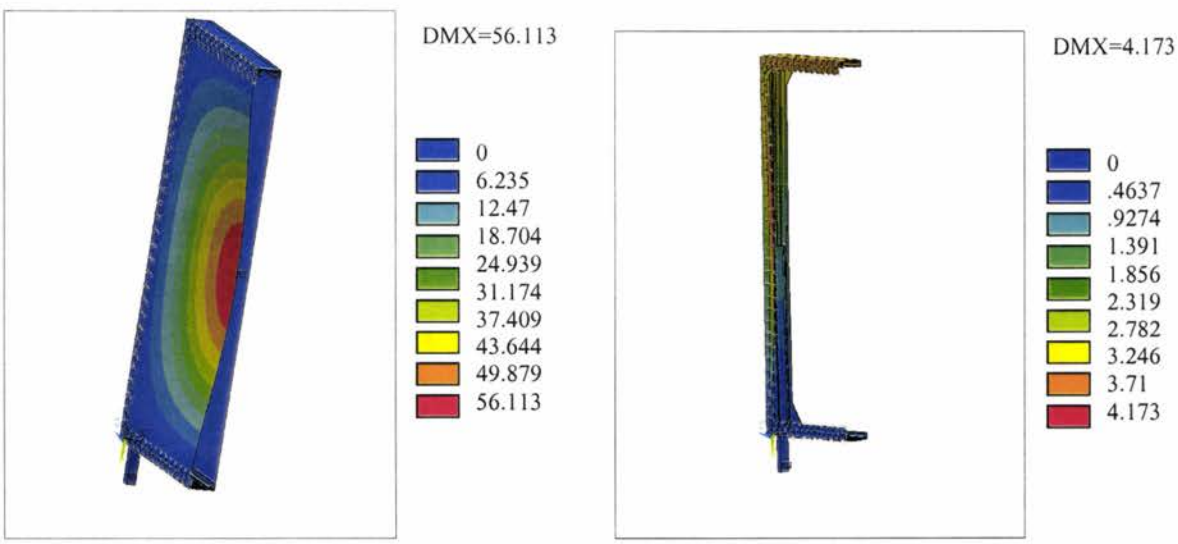


Fig. 7.8: Deflection of the frame and front panel of 122"x98" signboard

Rotation:

The rotation of the frame of tall model due to the wind pressure is observed to be 0.6 degrees (Fig. 7.9). The maximum rotation of the frame occurred on the surface approximately at the middle of the frame where the post begins. Since the rotation is of very low order it can be concluded that the frame is safe for rotation.

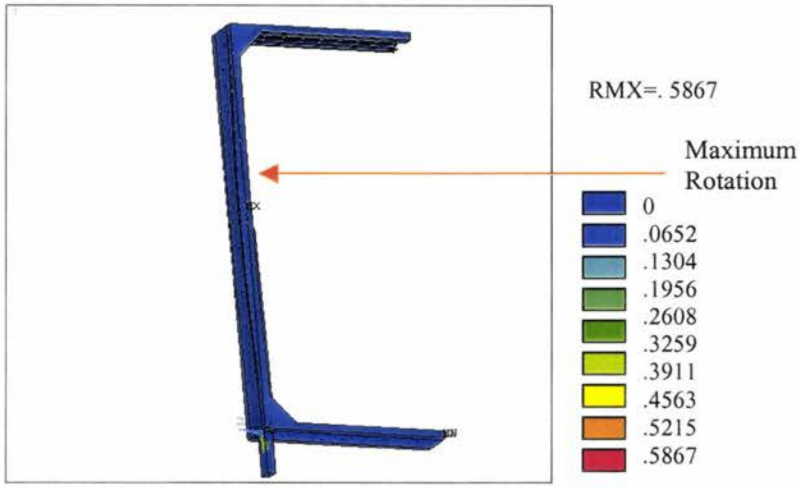


Fig. 7.9 Rotation in the frame of 122"x98' FE model

Tensile stress:

The maximum tensile stress of the frame is 86817 *psi*. It occurred at the point where the frame carrying the post and the outer section of the frame gets in contact. The tensile stress distribution and maximum value of tensile stress is represented in Fig. 7.10.

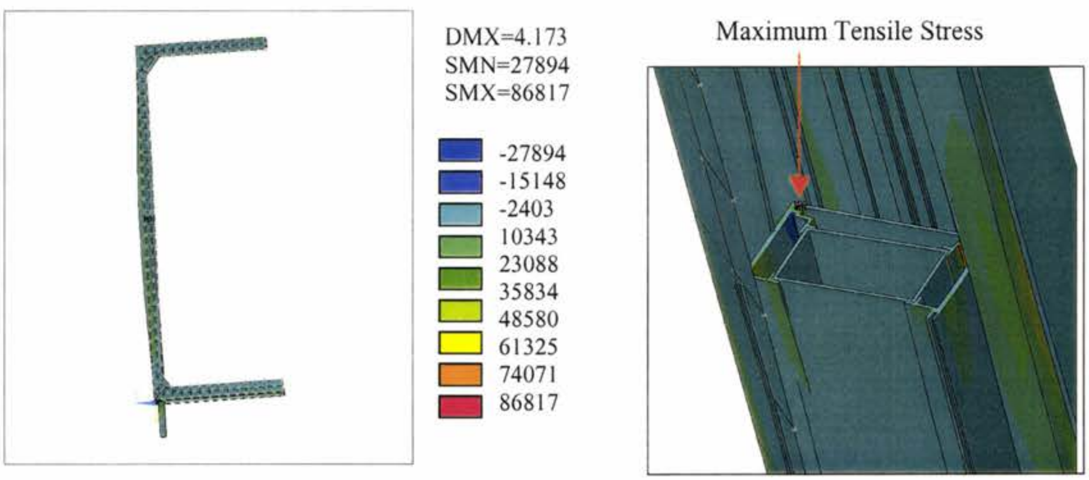


Fig. 7.10 Tensile stress distribution in the frame

Compressive Stress:

The maximum value of the stress in compression is obtained as 25,768 *psi*. The maximum compression occurs at a point roughly opposite to the point where the maximum value is the tensile stress is obtained. The Fig. 7.11 gives an idea of the distribution of compressive stresses on the frame.

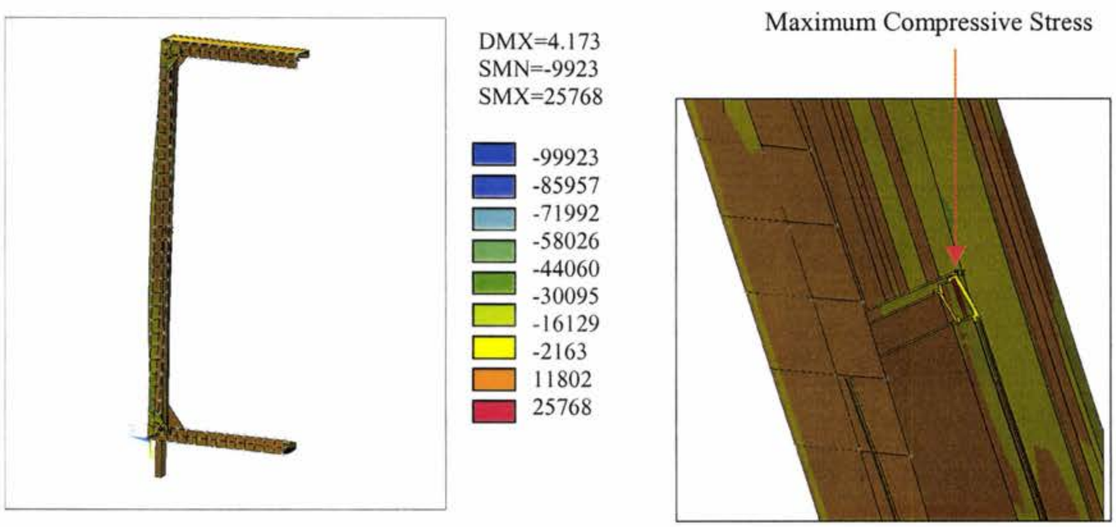


Fig. 7.11 Compressive stress variation in the frame

Shear Stress:

The shear stresses in the frame lie in the safe limit. The maximum shear stress in the frame is observed to be 30,311 *psi* in the YZ-Plane. This is a very high value of stress and can be reduced by increasing the length of the post. Fig. 7.12.1 shows the shear stress distribution in XY, YZ directions and Fig.7.12.2 indicated in the XZ direction.

Fig. 7.12.1 Shear stress distribution of 122"x98" in XY, YZ planes

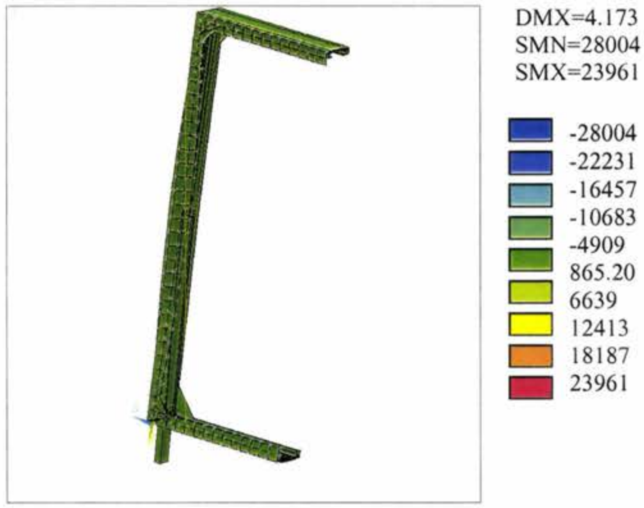


Fig. 7.12.2 Shear stress distribution of 122"x98" in XZ plane

von-Mises stress:

A von-Mises stress value of 112,360 *psi* occurred at a corner point where the post enters the frame from the ground, Fig. 7.13. As the factor of safety for the von-Mises stress is considerably low these values have to be improved before the signboard can be considered safe. Various suggestions are presented to achieve a high safety level.

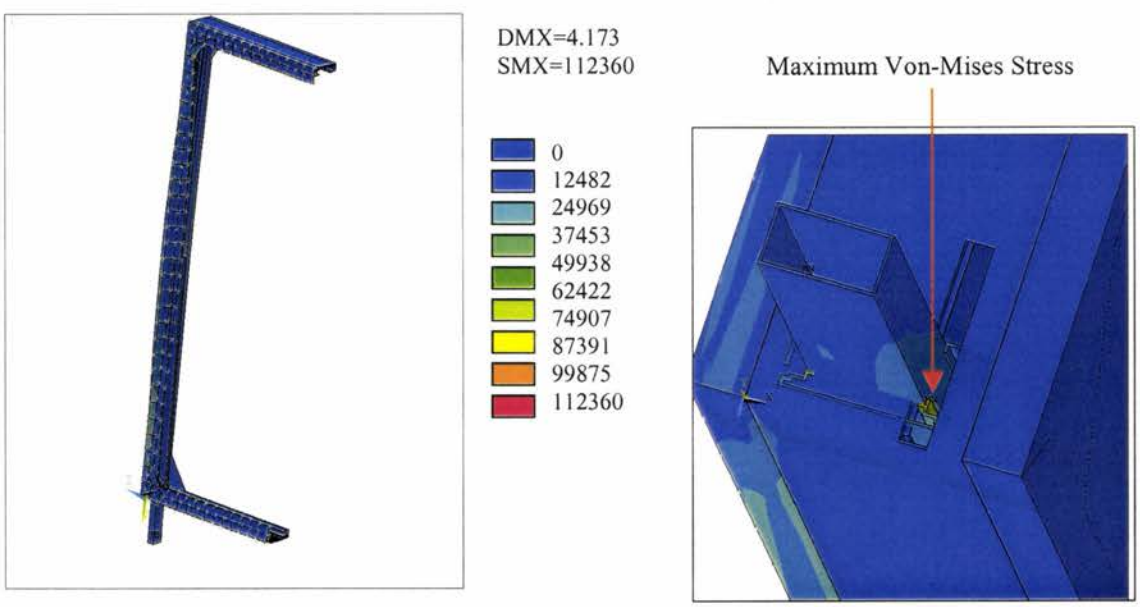


Fig. 7.13 von-Mises stress distribution in the frame

Summary of the Results for 122”x98” Signboard:

Maximum displacement in the panel = 56.1”

Maximum displacement of the frame = 3.41”

Maximum von-Mises stress = 112360 *psi*

Maximum principal tensile stress = 86817 *psi*

Maximum principal compressive stress = 25768 *psi*

Maximum shear stress = 27211 *psi*

CHAPTER 8

ANALYSIS OF RESULTS

High values of the deflections of the front panels of both the models can be attributed for the following reasoning. The FE analysis of both the models was carried out for a small deflection analysis. Since the boards are huge and have high dimensions the various effects of the internal forces action on the boards should be considered for the analysis. During the analysis of a large two-dimensional plate it should be noted that the lateral loading is partly supported by its bending resistance and partly by the involvement of the membrane action. This leads to the large deflection analysis of the boards. A quick theoretical analysis taking the effects of the various internal stresses acting on the board into consideration gives us the solution for this problem.

Approximate solution for the maximum displacement (w_{max}) of the large deflection problem can be obtained by solving the following equation (8.1)[8].

$$\frac{pa^4}{Et^4} = \frac{1}{a}\left(\frac{w_{max}}{t}\right)\left(\frac{a}{b}\right)^4 + \frac{1}{n_1^3}\left(\frac{w_{max}}{t}\right)^3 \tag{8.1}$$

where,

Pressure (p) = 0.2035 *psi*

Width of the board (a) = 144"

Height of the board (b) = 50"

Modulus of Elasticity (E) = 1181.4 *ksi*

Thickness of the sheet (t) = 0.1875"

Coefficient of deflection (n_1) = 0.318

The corresponding value of n_1 with an aspect ratio (a/b) of 2.32 was obtained from the following table[9].

Table 8.1 Deflection Coefficients based on aspect ratio[9]

Membrane Stress and Deflection Coefficients							
a/b	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**4.0**	**5.0**
n_1	0.318	0.228	0.160	0.125	0.100	0.068	0.052
n_2	0.356	0.370	0.336	0.304	0.272	0.230	0.205

Solving the above relation for w_{max}, the maximum displacement of the front panel of the 122"x98" signboard was obtained as **1.589"** and the maximum displacement of 50"x144" signboard was obtained as **0.768"**.

8.1 Large displacement analysis

Modeling of the frame:

This analysis of large displacement of plates could not be carried out for the FE models because of the complicated cross-section of the boards. Hence a simple FE analysis of the front panel alone was carried on in ANSYS. The front sheet was modeled using key points and areas and was then subjected to free mesh. The frame was fixed in all degrees of freedom on all the four corners and then a uniform average pressure of 0.2035 *psi* was applies and the analysis were carried out for large displacement.

Analysis of the 50"x144" front sheet:

The maximum deflection of the 50"x144" model was observed to be 0.578" and occurred at the middle of the sheet. This is very close to the value of the displacement obtained theoretically which is 0.768". Fig. 8.1 indicates the displacement variation in the frame of 50"x144" signboard.

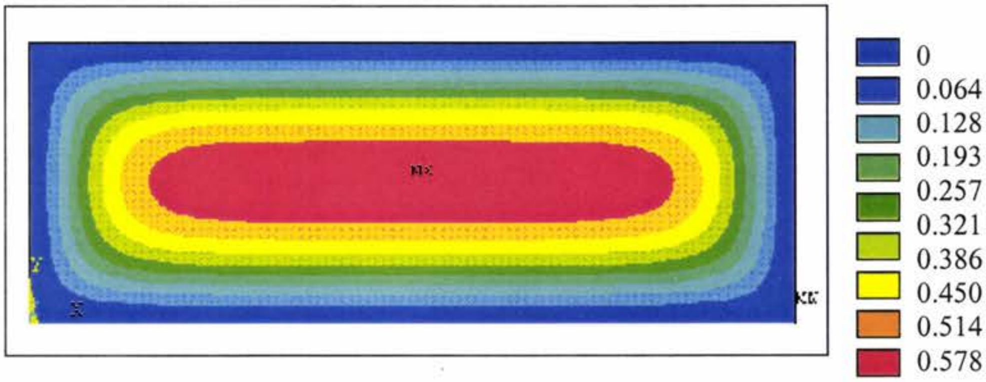


Fig. 8.1 Large displacement analysis of front panel of 50"x144" signboard

Analysis of the 122"x98" front sheet:

The maximum deflection of the 122"x98" model was observed to be 1.367" also occurring at the middle of the sheet, Fig.8.2. This is very close to the value of the displacement obtained theoretically which is 1.589".

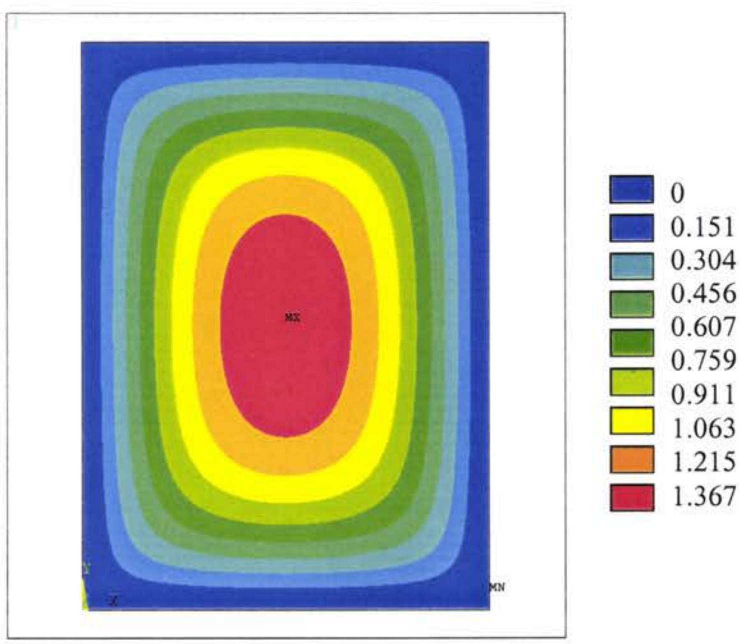


Fig.8.2 Large Displacement Analysis of the front panel122'x98" signboard

Hence, when the FE analysis of the entire model is carried out taking care of the concepts of large displacement of plates, the deflection of the entire board may reduce when compared to the results obtained with the small displacement analysis. This also reduces the stresses acting on the board to a higher extent.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

The results obtained for all models, when subjected to a wind pressure of 100 *mph* are tabulated as follows. Table: 9.1, indicates the summary of results of the 50"x144" signboard and 122"x98" signboard having the actual cross-section obtained through the FE analysis. Table: 9.2, indicates the summary of results of all the reduced models with post and bolt fastening. Table 9.3, gives the summary of the large displacement analysis of frames of both the models of signboard. Based on the results obtained and in comparison to the maximum allowable stress limits of the materials, aluminum and fiberglass, recommendations on the design were made.

Table: 9.1 Results of 50"x144" and 122"x98" signboards with original cross section

	Frame displacement (*in*)	Panel displacement (*in*)	Max tensile stress (*psi*)	Max compressive stress (*psi*)	Max shear stress (psi)	Max von-Mises stress (*psi*)
50"x144" signboard	0.99	5.15	35,694	14,637	16955	34,262
122"x98" signboard	4.17	56.11	86,817	25,768	30,311	112,360

Table: 9.2 Results of 50"144" and 122"x98" Reduced Models

	Frame displacement (*in*)	Panel displacement (*in*)	Max von-mises stress (*psi*)
50"x144" (with post)	0.58	5.98	51,632
50"x144" signboard (no post)	0.19	6.85	8,60
50"x144" signboard with central support (no post)	0.57 (on the central support)	5.72	26,559
122"x98" signboard (no post)	12.14	88.65	222,654

Table: 9.3 Summary of the results of large displacement analysis

Displacement of the frame *(in)*		
	Theoretical value	**Computed Value**
50”x144”	0.768”	0.578”
122”x98”	1.589”	1.367”

9.1 Conclusions

122”98” FE Model:

From the results obtained for the actual models it can be seen that the 122”x98” model has a very high value of frame deflection of the order of 4.17” and panel deflection of 56.11”. If the deflections of the frame and panel are so high then besides the frame failing, the internal lighting fixtures of the board are damaged. Also, the von-Mises stress and the shear stress are considerably high.

But from the theory of large displacement analysis, when a uniform pressure is acting on a plate with high dimensions then there exists interior stiffening of the structure due to the huge deflection. If the interior stiffening of the front panel sheet alone could reduce the deflection from 56.11” to 1.37” then it can be assumed that when the analysis of the entire structure is performed the total deflection might be a much lower value.

50”x144” FE Model:

The deflection of the front panel is of the order of 5.15”. Again, this high value of deflection is due to the small deflection analysis. When the large displacement analysis is carried out on this model the displacement might be reduced to a higher degree. As discussed earlier, if the displacement of the plate alone with the large displacement analysis is reduced to 0.6” from 5.15” then when the FE analysis of the entire model is performed the total deflection would be much less due to the internal stiffening of the structure.

Also, it can be observed that the stresses are mainly concentrated at the point where the post is entering the frame. Appropriate recommendations for this are provided to ensure safe design.

Bolt & Anchor Models:

Based on the above analysis of the reduced frame it can be concluded that the design is good. The factors of safety of a wind speed of 100 *mph* are observed to be of the order of 6, which is highly safe for the design. For the model with bolt and anchor design, basing on the loads on the bolts proper anchors can be used.

The deflection of the frame and the panel for the 122"x98" dimension signboard with the bots design was observed to be very high. The large displacement analysis used for models with posts can be assumed here. As mentioned above, the large displacement analysis can be applied here.

9.2 Recommendations

Models with Posts:

For both the models with posts, it is suggested that the post should be made longer and mounted higher than the present, say to about 75% of the height of the frame to reduce the stress concentrations at the point where the post enters. This will even out the load distribution and the peak stresses at the top of the posts. Also, using doubler plates at the bottom where the post enters the frame can reduce the von-Mises stresses.

For the 50"x144" signboard, it is recommended that a vertical central support be added in the frame as an additional support to reduce any possible vibrations in the frame. For the 122"x98" board, including horizontal braces would aid in strengthening the frame.

Bolt & Anchor Models:

Adding a doubler plate at the bottom can reduce the high value of the deflection in the frame in both wide and tall models. Also, the deflection in the front panel can be reduced further increasing the thickness of the existing fiberglass sheet. Adding a central support horizontally to the tall frame and vertically to the wide frame can increase the stiffness of the model.

It has to be kept in mind that since the panels have transparent wordings for the light to shine through, the central supports have to be designed on a case-by-case basis.

APPENDIX

A.1 Text files for FE model generation:

Side Part 1

```
/PREP7
ET,1,SOLID45
WPROTA,90,-270,-90
CSYS,WP
WPAVE,-3.78,0,122
CSYS,WP
*GET,NS1,NODE,,NUM,MAX
N,NS1+1,0.00,0.00,-122.
N,NS1+2,0.0,-.16,-121.8
N,NS1+3,0.00,-0.50,-121.5.
N,NS1+4,-0.38,-0.50,-121.5.
N,NS1+5,-.38,-.16,-121.8
N,NS1+6,-0.51,-0.16,-121.8.
N,NS1+7,-0.83,-0.16,-121.8.
N,NS1+8,-.83,-.42,-121.6
N,NS1+9,-0.83,-0.51,-121.5.
N,NS1+10,-.93,-.51,-121.5
N,NS1+11,-1.14,-0.51,-121.5.
N,NS1+12,-1.14,-0.42,-121.6.
N,NS1+13,-0.93,-0.42,-121.6.
N,NS1+14,-0.93,-0.16,-121.8.
N,NS1+16,-1.84,-0.16,-121.8.
FILL
N,NS1+17,-1.84,-0.42,-121.6.
N,NS1+18,-1.73,-.42,-121.6
N,NS1+19,-1.63,-0.42,-121.6.
N,NS1+20,-1.63,-.52,-121.5
N,NS1+21,-1.63,-0.64,-121.4.
N,NS1+22,-1.73,-0.64,-121.4.
N,NS1+23,-1.73,-0.52,-121.5.
N,NS1+24,-1.84,-0.52,-121.5.
N,NS1+28,-1.84,-2.0,-120.
FILL,NS1+24,NS1+28
N,NS1+29,-2.06,-2.0,-120.
N,NS1+33,-2.06,-.52,-121.5
FILL
N,NS1+34,-2.06,-.42,-121.6
N,NS1+35,-2.06,-.16,-121.8
N,NS1+36,-2.06,0.0,-122.
N,NS1+37,-1.84,0,-122
N,NS1+39,-.93,0,-122
FILL
N,NS1+40,-.83,0,-122
N,NS1+41,-.51,0,-122
N,NS1+42,-.38,0,-122
!OTHER SIDE
NDIV=30
NLST=NS1+42*NDIV
N,NLST+1,0.0,0.0,0.0
N,NLST+2,0,-.16,-.16
N,NLST+3,0.0,-0.50,-0.50
N,NLST+4,-0.38,-0.50,-0.50
N,NLST+5,-.38,-.16,-.16
N,NLST+6,-0.51,-0.16,-0.16
N,NLST+7,-0.83,-0.16,-0.16
N,NLST+8,-.83,-.42,-.42
N,NLST+9,-0.83,-0.51,-0.51
N,NLST+10,-.93,-.51,-.51
N,NLST+11,-1.14,-0.51,-0.51
N,NLST+12,-1.14,-0.42,-0.42
N,NLST+13,-0.93,-0.42,-0.42
N,NLST+14,-0.93,-0.16,-0.16
N,NLST+16,-1.84,-0.16,-0.16
FILL
N,NLST+17,-1.84,-0.42,-0.42
N,NLST+18,-1.73,-.42,-.42
N,NLST+19,-1.63,-0.42,-0.42
N,NLST+20,-1.63,-.52,-.52
N,NLST+21,-1.63,-0.64,-0.64
N,NLST+22,-1.73,-0.64,-0.64
N,NLST+23,-1.73,-0.52,-0.52
N,NLST+24,-1.84,-0.52,-0.52
N,NLST+28,-1.84,-2.0,-2.0
FILL
N,NLST+29,-2.06,-2.0,-2.0
N,NLST+33,-2.06,-.52,-.52
FILL
N,NLST+34,-2.06,-.42,-.42
N,NLST+35,-2.06,-.16,-.16
N,NLST+36,-2.06,0.0,0.0
N,NLST+37,-1.84,0,0
N,NLST+39,-.93,0,0
FILL
N,NLST+40,-.83,0,0
N,NLST+41,-.51,0,0
N,NLST+42,-.38,0,0
FILL,NS1+1,NLST+1,NDIV-1,,42
*REPEAT,42,1,1
*GET,EN1,ELEM,,NUM,MAX
E,NS1+1,NS1+2,NS1+5,NS1+42,NS1+43,NS1+44,NS1+47,NS1+84
E,NS1+2,NS1+3,NS1+4,NS1+5,NS1+44,NS1+45,NS1+46,NS1+47
E,NS1+5,NS1+6,NS1+41,NS1+42,NS1+47,NS1+48,NS1+83,NS1+84
E,NS1+6,NS1+7,NS1+40,NS1+41,NS1+48,NS1+49,NS1+82,NS1+83
E,NS1+7,NS1+14,NS1+39,NS1+40,NS1+49,NS1+56,NS1+81,NS1+82
E,NS1+8,NS1+13,NS1+14,NS1+7,NS1+50,NS1+55,NS1+56,NS1+49
E,NS1+9,NS1+10,NS1+13,NS1+8,NS1+51,NS1+52,NS1+55,NS1+50
E,NS1+10,NS1+11,NS1+12,NS1+13,NS1+52,NS1+53,NS1+54,NS1+55
E,NS1+14,NS1+15,NS1+38,NS1+39,NS1+56,NS1+57,NS1+80,NS1+81
E,NS1+15,NS1+16,NS1+37,NS1+38,NS1+57,NS1+58,NS1+79,NS1+80
E,NS1+16,NS1+35,NS1+36,NS1+37,NS1+58,NS1+77,NS1+78,NS1+79
E,NS1+17,NS1+34,NS1+35,NS1+16,NS1+59,NS1+76,NS1+77,NS1+58
E,NS1+24,NS1+33,NS1+34,NS1+17,NS1+66,NS1+75,NS1+76,NS1+59
E,NS1+23,NS1+24,NS1+17,NS1+18,NS1+65,NS1+66,NS1+59,NS1+60
E,NS1+20,NS1+23,NS1+18,NS1+19,NS1+62,NS1+65,NS1+60,NS1+61
E,NS1+21,NS1+22,NS1+23,NS1+20,NS1+63,NS1+64,NS1+65,NS1+62
E,NS1+25,NS1+32,NS1+33,NS1+24,NS1+67,NS1+74,NS1+75,NS1+66
E,NS1+25,NS1+26,NS1+31,NS1+32,NS1+67,NS1+68,NS1+73,NS1+74
E,NS1+26,NS1+27,NS1+30,NS1+31,NS1+68,NS1+69,NS1+72,NS1+73
E,NS1+27,NS1+28,NS1+29,NS1+30,NS1+69,NS1+70,NS1+71,NS1+72
*GET,EN2,ELEM,,NUM,MAX
EGEN,NDIV,42,EN1+1,EN2,1
```

Side Part 2:

/PREP7	N,NN2S+22,-1.75,-0.35,-0.35
ET,1,SOLID45	N,NN2S+23,-1.55,-0.35,-0.35
WPAVE,3.78,0,0	N,NN2S+24,-1.55,-0.12,-0.12
CSYS,WP	N,NN2S+28,-3.52,-0.12,-0.12
*GET,NS2,NODE,,NUM,MAX	FILL
N,NS2+1,0.0,0.0,-122.	N,NN2S+29,-3.52,-0.32,-0.32
N,NS2+2,0.0,-0.12,-121.9.	N,NN2S+30,-3.02,-0.32,-0.32
N,NS2+3,-0.25,-0.12,-121.9.	NN2S+31,-3.02,-0.45,-0.45
N,NS2+4,-0.25,-0.35,-121.7.	N,NN2S+32,-3.52,-0.45,-0.45
N,NS2+5,-0.125,-0.35,-121.7.	N,NN2S+33,-3.52,-0.71,-0.71
N,NS2+6,-0.125,-0.45,-121.6.	
,NS2+7,-.25,-.45,-121.6	N,NN2S+34,-3.02,-0.71,-0.71
N,NS2+8,-.35,-.45,-121.6	N,NN2S+35,-3.02,-0.84,-0.84
N,NS2+9,-0.475,-0.45,-121.6.	N,NN2S+36,-3.52,-0.84,-0.84
N,NS2+10,-0.475,-0.35,-121.7.	NN2S+37,-3.76,-0.91,-0.91
N,NS2+11,-0.35,-0.35,-121.6.	N,NN2S+38,-4.31,-.91,-.91
N,NS2+12,-0.35,-0.12,-121.9.	N,NN2S+39,-4.5,-0.91,-0.91
N,NS2+15,-1.45,-0.12,-121.9.	N,NN2S+42,-4.5,-1.98,-1.98
FILL	FILL
N,NS2+16,-1.45,-0.35,-121.7.	N,NN2S+45,-2.92,-1.98,-1.98
NS2+17,-1.25,-0.35,-121.7.	FILL
N,NS2+18,-1.25,-0.45,-121.5.	N,NN2S+46,-2.92,-2.1,-2.1
N,NS2+19,-1.45,-.45,-121.5	N,NN2S+49,-4.5,-2.1,-2.1
N,NS2+20,-1.55,-.45,-121.5	FILL
N,NS2+21,-1.75,-0.45,-121.5.	N,NN2S+50,-4.62,-2.1,-2.1
N,NS2+22,-1.75,-0.35,-121.7.	N,NN2S+51,-4.62,-1.98,-1.98
N,NS2+23,-1.55,-0.35,-121.6.	N,NN2S+54,-4.62,-.91,-.91
N,NS2+24,-1.55,-0.12,-121.9.	FILL
N,NS2+28,-3.52,-0.12,-121.9.	N,NN2S+55,-4.62,-.75,-.75
FILL	N,NN2S+57,-4.62,-0.16,-0.16
N,NS2+29,-3.52,-0.32,-121.7.	FILL
N,NS2+30,-3.02,-0.32,-121.7.	N,NN2S+58,-4.31,-0.16,-0.16
N,NS2+31,-3.02,-0.45,-121.5.	NN2S+60,-4.31,-0.75,-0.75
N,NS2+32,-3.52,-0.45,-121.5.	FILL
N,NS2+33,-3.52,-0.71,-121.3.	N,NN2S+61,-3.76,-0.75,-0.75
N,NS2+34,-3.02,-0.71,-121.3.	N,NN2S+62,-3.76,-.45,-.45
N,NS2+35,-3.02,-0.84,-121.2.	NN2S+63,-3.76,-.32,-.32
N,NS2+36,-3.52,-0.84,-121.2.	N,NN2S+64,-3.76,-.12,-.12
N,NS2+37,-3.76,-0.91,-121.1.	N,NN2S+65,-3.76,0.0,0.0
N,NS2+38,-4.31,-.91,-121.1	N,NN2S+66,-3.52,0,0
N,NS2+39,-4.5,-0.91,-121.1.	N,NN2S+70,-1.55,0,0
N,NS2+42,-4.5,-1.98,-120.	FILL
FILL	N,NN2S+71,-1.45,0,0
N,NS2+45,-2.92,-1.98,-120.	N,NN2S+74,-.35,0,0
FILL	FILL
N,NS2+46,-2.92,-2.1,-119.9.	N,NN2S+75,-.25,0,0
N,NS2+49,-4.5,-2.1,-119.9	! NOW FILL
FILL	FILL,NS2+1,NN2S+1,NDIV-1,,75
N,NS2+50,-4.62,-2.1,-119.9.	*REPEAT,75,1,1
N,NS2+51,-4.62,-1.98,-120	*GET,ENS2,ELEM,,NUM,MAX
N,NS2+54,-4.62,-.91,-121.1	E,NS2+1,NS2+2,NS2+3,NS2+75,NS2+76,NS2+77,NS2+78,NS2+150
FILL	E,NS2+3,NS2+12,NS2+74,NS2+75,NS2+78,NS2+87,NS2+149,NS2+150
N,NS2+55,-4.62,-.75,-121.2	E,NS2+3,NS2+4,NS2+11,NS2+12,NS2+78,NS2+79,NS2+86,NS2+87
N,NS2+57,-4.62,-0.16,-121.8	E,NS2+5,NS2+6,NS2+7,NS2+4,NS2+80,NS2+81,NS2+82,NS2+79
FILL	E,NS2+7,NS2+8,NS2+11,NS2+4,NS2+82,NS2+83,NS2+86,NS2+79
N,NS2+58,-4.31,-0.16,-121.8	E,NS2+8,NS2+9,NS2+10,NS2+11,NS2+83,NS2+84,NS2+85,NS2+86
N,NS2+60,-4.31,-0.75,-121.2	E,NS2+12,NS2+13,NS2+73,NS2+74,NS2+87,NS2+88,NS2+148,NS2+149
FILL	E,NS2+13,NS2+14,NS2+72,NS2+73,NS2+88,NS2+89,NS2+147,NS2+148
N,NS2+61,-3.76,-0.75,-121.2	E,NS2+14,NS2+15,NS2+71,NS2+72,NS2+89,NS2+90,NS2+146,NS2+147
N,NS2+62,-3.76,-.45,-121.5	E,NS2+15,NS2+24,NS2+70,NS2+71,NS2+90,NS2+99,NS2+145,NS2+146
N,NS2+63,-3.76,-.32,-121.7	E,NS2+15,NS2+16,NS2+23,NS2+24,NS2+90,NS2+91,NS2+98,NS2+99
N,NS2+64,-3.76,-.12,-121.9	E,NS2+17,NS2+18,NS2+19,NS2+16,NS2+92,NS2+93,NS2+94,NS2+91
N,NS2+65,-3.76,0.0,-122.	E,NS2+16,NS2+19,NS2+20,NS2+23,NS2+91,NS2+94,NS2+95,NS2+98
N,NS2+66,-3.52,0,-122	E,NS2+20,NS2+21,NS2+22,NS2+23,NS2+95,NS2+96,NS2+97,NS2+98

N,NS2+70,-1.55,0,-122 FILL N,NS2+71,-1.45,0,-122 N,NS2+74,-.35,0,-122 FILL N,NS2+75,-.25,0,-122 !OTHER SIDE NDIV=30 N2S=NS2+75*NDIV N,NN2S+1,0.0,0.0,0.0 N,NN2S+2,0.0,-0.12,-0.12 N,NN2S+3,-0.25,-0.12,-0.12 N,NN2S+4,-0.25,-0.35,-0.35 N,NN2S+5,-0.125,-0.35,-0.35 N,NN2S+6,-0.125,-0.45,-0.45 N,NN2S+7,-.25,-.45,-.45 N,NN2S+8,-.35,-.45,-.45 N,NN2S+9,-0.475,-0.45,-0.45 N,NN2S+10,-0.475,-0.35,-0.35 N,NN2S+11,-0.35,-0.35,-0.35 N,NN2S+12,-0.35,-0.12,-0.12 N,NN2S+15,-1.45,-0.12,-0.12 FILL N,NN2S+16,-1.45,-0.35,-0.35 N,NN2S+17,-1.25,-0.35,-0.35 N,NN2S+18,-1.25,-0.45,-0.45 N,NN2S+19,-1.45,-.45,-.45 N,NN2S+20,-1.55,-.45,-.45 N,NN2S+21,-1.75,-0.45,-0.45	E,NS2+24,NS2+25,NS2+69,NS2+70,NS2+99,NS2+100,NS2+144,NS2+145 E,NS2+25,NS2+26,NS2+68,NS2+69,NS2+100,NS2+101,NS2+143,NS2+144 E,NS2+26,NS2+27,NS2+67,NS2+68,NS2+101,NS2+102,NS2+142,NS2+143 E,NS2+27,NS2+28,NS2+66,NS2+67,NS2+102,NS2+103,NS2+141,NS2+142 E,NS2+28,NS2+64,NS2+65,NS2+66,NS2+103,NS2+139,NS2+140,NS2+141 E,NS2+29,NS2+63,NS2+64,NS2+28,NS2+104,NS2+138,NS2+139,NS2+103 E,NS2+29,NS2+32,NS2+62,NS2+63,NS2+104,NS2+107,NS2+137,NS2+138 E,NS2+30,NS2+31,NS2+32,NS2+29,NS2+105,NS2+106,NS2+107,NS2+104 E,NS2+32,NS2+33,NS2+61,NS2+62,NS2+107,NS2+108,NS2+136,NS2+137 E,NS2+33,NS2+36,NS2+37,NS2+61,NS2+108,NS2+111,NS2+112,NS2+136 E,NS2+34,NS2+35,NS2+36,NS2+33,NS2+109,NS2+110,NS2+111,NS2+108 E,NS2+61,NS2+37,NS2+38,NS2+60,NS2+136,NS2+112,NS2+113,NS2+135 E,NS2+38,NS2+39,NS2+60,NS2+60,NS2+113,NS2+114,NS2+135,NS2+135 E,NS2+60,NS2+39,NS2+54,NS2+55,NS2+135,NS2+114,NS2+129,NS2+130 E,NS2+39,NS2+40,NS2+53,NS2+54,NS2+114,NS2+115,NS2+128,NS2+129 E,NS2+40,NS2+41,NS2+52,NS2+53,NS2+115,NS2+116,NS2+127,NS2+128 E,NS2+41,NS2+42,NS2+51,NS2+52,NS2+116,NS2+117,NS2+126,NS2+127 E,NS2+42,NS2+49,NS2+50,NS2+51,NS2+117,NS2+124,NS2+125,NS2+126 E,NS2+42,NS2+43,NS2+48,NS2+49,NS2+117,NS2+118,NS2+123,NS2+124 E,NS2+43,NS2+44,NS2+47,NS2+48,NS2+118,NS2+119,NS2+122,NS2+123 E,NS2+44,NS2+45,NS2+46,NS2+47,NS2+119,NS2+120,NS2+121,NS2+122 E,NS2+60,NS2+55,NS2+56,NS2+59,NS2+135,NS2+130,NS2+131,NS2+134 E,NS2+59,NS2+56,NS2+57,NS2+58,NS2+134,NS2+131,NS2+132,NS2+133 *GET,ENN2S,ELEM,,NUM,MAX EGEN,NDIV,75,ENS2+1,ENN2S,1

Side Part 3:

/PREP7 ET,1,SOLID45 WPAVE,0,-.71,-.0 CSYS,WP *GET,N3S,NODE,,NUM,MAX N,N3S+1,0,0,-122 N,N3S+2,0,-0.1,-122 N,N3S+3,-0.45167,-0.1,-122 N,N3S+4,-0.90333,-0.1,-122 N,N3S+5,-1.355,-0.1,-122 N,N3S+6,-1.8067,-0.1,-122 N,N3S+7,-2.2583,-0.1,-122 N,N3S+8,-2.71,-0.1,-122 N,N3S+9,-2.71,-0.21,-122 N,N3S+10,-2.6,-0.21,-122 N,N3S+11,-2.46,-0.21,-122 N,N3S+12,-2.46,-0.36,-122 N,N3S+13,-2.13,-0.36,-122 N,N3S+14,-2.03,-0.36,-122 N,N3S+15,-2.03,-0.46,-122 N,N3S+16,-2.03,-0.61,-122 N,N3S+17,-1.78,-0.61,-122 N,N3S+18,-1.78,-0.71,-122 N,N3S+19,-2.03,-0.71,-122 N,N3S+20,-2.03,-0.96,-122 N,N3S+21,-2.13,-0.96,-122 N,N3S+22,-2.13,-0.71,-122 N,N3S+23,-2.13,-0.61,-122 N,N3S+24,-2.13,-0.46,-122 N,N3S+25,-2.46,-0.46,-122 N,N3S+26,-2.6,-0.46,-122 N,N3S+27,-2.6,-0.36,-122 N,N3S+28,-2.71,-0.36,-122 N,N3S+29,-2.71,-0.70857,-122 N,N3S+30,-2.71,-1.0571,-122 N,N3S+31,-2.71,-1.4057,-122	 N,N3E+18,-1.78,-0.71,-61 N,N3E+19,-2.03,-0.71,-61 N,N3E+20,-2.03,-0.96,-61 N,N3E+21,-2.13,-0.96,-61 N,N3E+22,-2.13,-0.71,-61 N,N3E+23,-2.13,-0.61,-61 N,N3E+24,-2.13,-0.46,-61 N,N3E+25,-2.46,-0.46,-61 N,N3E+26,-2.6,-0.46,-61 N,N3E+27,-2.6,-0.36,-61 N,N3E+28,-2.71,-0.36,-61 N,N3E+29,-2.71,-0.70857,-61 N,N3E+30,-2.71,-1.0571,-61 N,N3E+31,-2.71,-1.4057,-61 N,N3E+32,-2.71,-1.7543,-61 N,N3E+33,-2.71,-2.1029,-61 N,N3E+34,-2.71,-2.4514,-61 ,N3E+35,-2.71,-2.8,-61 N,N3E+36,-2.13,-2.8,-61 N,N3E+37,-2.13,-2.55,-61 N,N3E+38,-2.03,-2.55,-61 N,N3E+39,-2.03,-2.8,-61 N,N3E+40,-1.78,-2.8,-61 N,N3E+41,-1.78,-2.9,-61 N,N3E+42,-2.03,-2.9,-61 N,N3E+43,-2.13,-2.9,-61 N,N3E+44,-2.61,-2.9,-61 N,N3E+45,-2.61,-2.97,-61 N,N3E+46,-2.61,-3.25,-61 N,N3E+47,-2.71,-3.25,-61 N,N3E+48,-2.71,-2.97,-61 N,N3E+49,-2.81,-2.97,-61 N,N3E+50,-2.81,-3.25,-61 N,N3E+51,-2.87,-3.25,-61 N,N3E+52,-2.87,-2.97,-61

```
N,N3S+32,-2.71,-1.7543,-122
N,N3S+33,-2.71,-2.1029,-122
N,N3S+34,-2.71,-2.4514,-122
N,N3S+35,-2.71,-2.8,-122
N,N3S+36,-2.13,-2.8,-122
N,N3S+37,-2.13,-2.55,-122
N,N3S+38,-2.03,-2.55,-122
N,N3S+39,-2.03,-2.8,-122
N,N3S+40,-1.78,-2.8,-122
N,N3S+41,-1.78,-2.9,-122
N,N3S+42,-2.03,-2.9,-122
N,N3S+43,-2.13,-2.9,-122
N,N3S+44,-2.61,-2.9,-122
N,N3S+45,-2.61,-2.97,-122
N,N3S+46,-2.61,-3.25,-122
N,N3S+47,-2.71,-3.25,-122
N,N3S+48,-2.71,-2.97,-122
N,N3S+49,-2.81,-2.97,-122
N,N3S+50,-2.81,-3.25,-122
N,N3S+51,-2.87,-3.25,-122
N,N3S+52,-2.87,-2.97,-122
N,N3S+53,-2.87,-2.8,-122
N,N3S+54,-2.87,-2.4514,-122
N,N3S+55,-2.87,-2.1029,-122
N,N3S+56,-2.87,-1.7543,-122
N,N3S+57,-2.87,-1.4057,-122
N,N3S+58,-2.87,-1.0571,-122
N,N3S+59,-2.87,-0.70857,-122
N,N3S+60,-2.87,-0.36,-122
N,N3S+61,-2.87,-0.21,-122
N,N3S+62,-2.87,-0.1,-122
N,N3S+63,-2.87,0,-122
N,N3S+64,-2.71,0,-122
N,N3S+65,-2.2583,0,-122
N,N3S+66,-1.8067,0,-122
N,N3S+67,-1.355,0,-122
N,N3S+68,-0.90333,0,-122
N,N3S+69,-0.45167,0,-122
!OTHER SIDE  NDIV=15
N3E=N3S+69*NDIV
N,N3E+1,0,0,-61
N,N3E+2,0,-0.1,-61
N,N3E+3,-0.45167,-0.1,-61
N,N3E+4,-0.90333,-0.1,-61
N,N3E+5,-1.355,-0.1,-61
N,N3E+6,-1.8067,-0.1,-61
N,N3E+7,-2.2583,-0.1,-61
N,N3E+8,-2.71,-0.1,-61
N,N3E+9,-2.71,-0.21,-61
N,N3E+10,-2.6,-0.21,-61
N,N3E+11,-2.46,-0.21,-61
N,N3E+12,-2.46,-0.36,-61
N,N3E+13,-2.13,-0.36,-61
N,N3E+14,-2.03,-0.36,-61
N,N3E+15,-2.03,-0.46,-61
N,N3E+16,-2.03,-0.61,-61
N,N3E+17,-1.78,-0.61,-61
```

```
N,N3E+53,-2.87,-2.8,-61
N,N3E+54,-2.87,-2.4514,-61
N,N3E+55,-2.87,-2.1029,-61
N,N3E+56,-2.87,-1.7543,-61
N,N3E+57,-2.87,-1.4057,-61
N,N3E+58,-2.87,-1.0571,-61
N,N3E+59,-2.87,-0.70857,-61
N,N3E+60,-2.87,-0.36,-61
N,N3E+61,-2.87,-0.21,-61
N,N3E+62,-2.87,-0.1,-61
N,N3E+63,-2.87,0,-61
N,N3E+64,-2.71,0,-61
N,N3E+65,-2.2583,0,-61
N,N3E+66,-1.8067,0,-61
N,N3E+67,-1.355,0,-61
N,N3E+68,-0.90333,0,-61
N,N3E+69,-0.45167,0,-61
FILL,N3S+1,N3E+1,NDIV-1,,69
*REPEAT,69,1,1 *GET,EN1,ELEM,,NUM,MAX
E,N3S+1,N3S+2,N3S+3,N3S+69,N3S+70,N3S+71,N3S+72,N3S+138
E,N3S+3,N3S+4,N3S+68,N3S+69,N3S+72,N3S+73,N3S+137,N3S+138
E,N3S+4,N3S+5,N3S+67,N3S+68,N3S+73,N3S+74,N3S+136,N3S+137
E,N3S+5,N3S+6,N3S+66,N3S+67,N3S+74,N3S+75,N3S+135,N3S+136
E,N3S+6,N3S+7,N3S+65,N3S+66,N3S+75,N3S+76,N3S+134,N3S+135
E,N3S+7,N3S+8,N3S+64,N3S+65,N3S+76,N3S+77,N3S+133,N3S+134
E,N3S+8,N3S+62,N3S+63,N3S+64,N3S+77,N3S+131,N3S+132,N3S+133
E,N3S+9,N3S+61,N3S+62,N3S+8,N3S+78,N3S+130,N3S+131,N3S+77
E,N3S+28,N3S+60,N3S+61,N3S+9,N3S+97,N3S+129,N3S+130,N3S+78
E,N3S+10,N3S+27,N3S+28,N3S+9,N3S+79,N3S+96,N3S+97,N3S+78
E,N3S+11,N3S+12,N3S+27,N3S+10,N3S+80,N3S+81,N3S+96,N3S+79
E,N3S+12,N3S+25,N3S+26,N3S+27,N3S+81,N3S+94,N3S+95,N3S+96
E,N3S+13,N3S+24,N3S+25,N3S+12,N3S+82,N3S+93,N3S+94,N3S+81
E,N3S+14,N3S+15,N3S+24,N3S+13,N3S+83,N3S+84,N3S+93,N3S+82
E,N3S+15,N3S+16,N3S+23,N3S+24,N3S+84,N3S+85,N3S+92,N3S+93
E,N3S+16,N3S+19,N3S+22,N3S+23,N3S+85,N3S+88,N3S+91,N3S+92
E,N3S+17,N3S+18,N3S+19,N3S+16,N3S+86,N3S+87,N3S+88,N3S+85
E,N3S+19,N3S+20,N3S+21,N3S+22,N3S+88,N3S+89,N3S+90,N3S+91
E,N3S+28,N3S+29,N3S+59,N3S+60,N3S+97,N3S+98,N3S+128,N3S+129
E,N3S+29,N3S+30,N3S+58,N3S+59,N3S+98,N3S+99,N3S+127,N3S+128
E,N3S+30,N3S+31,N3S+57,N3S+58,N3S+99,N3S+100,N3S+126,N3S+127
E,N3S+31,N3S+32,N3S+56,N3S+57,N3S+100,N3S+101,N3S+125,N3S+126
E,N3S+32,N3S+33,N3S+55,N3S+56,N3S+101,N3S+102,N3S+124,N3S+125
E,N3S+33,N3S+34,N3S+54,N3S+55,N3S+102,N3S+103,N3S+123,N3S+124
E,N3S+34,N3S+35,N3S+53,N3S+54,N3S+103,N3S+104,N3S+122,N3S+123
E,N3S+35,N3S+36,N3S+43,N3S+44,N3S+104,N3S+105,N3S+112,N3S+113
E,N3S+36,N3S+39,N3S+42,N3S+43,N3S+105,N3S+108,N3S+111,N3S+112
E,N3S+36,N3S+37,N3S+38,N3S+39,N3S+105,N3S+106,N3S+107,N3S+108
E,N3S+40,N3S+41,N3S+42,N3S+39,N3S+109,N3S+110,N3S+111,N3S+108
E,N3S+35,N3S+44,N3S+45,N3S+48,N3S+104,N3S+113,N3S+114,N3S+117
E,N3S+45,N3S+46,N3S+47,N3S+48,N3S+114,N3S+115,N3S+116,N3S+117
E,N3S+35,N3S+48,N3S+49,N3S+49,N3S+104,N3S+117,N3S+118,N3S+118
E,N3S+49,N3S+50,N3S+51,N3S+52,N3S+118,N3S+119,N3S+120,N3S+121
E,N3S+53,N3S+49,N3S+52,N3S+52,N3S+122,N3S+118,N3S+121,N3S+121
E,N3S+35,N3S+49,N3S+53,N3S+53,N3S+104,N3S+118,N3S+122,N3S+122
*GET,EN2,ELEM,,NUM,MAX
EGEN,NDIV,69,EN1+1,EN2,1
```

Top Part 1:

```
/PREP7
ET,1,SOLID45
WPAVE,0,0,0
CSYS,WP
*GET,NN,NODE,,NUM,MAX
N,NN+1,0.00,0.00,-49.
N,NN+2,0.0,-.16,-49
N,NN+3,0.00,-0.50,-49.
N,NN+4,-0.38,-0.50,-49.
N,NN+5,-.38,-.16,-49
N,NN+6,-0.51,-0.16,-49.
N,NN+7,-0.83,-0.16,-49.
N,NN+8,-.83,-.42,-49
N,NN+9,-0.83,-0.51,-49.
N,NN+10,-.93,-.51,-49
N,NN+11,-1.14,-0.51,-49.
N,NN+12,-1.14,-0.42,-49.
N,NN+13,-0.93,-0.42,-49.
N,NN+14,-0.93,-0.16,-49.
N,NN+16,-1.84,-0.16,-49.
FILL
N,NN+17,-1.84,-0.42,-49.
N,NN+18,-1.73,-.42,-49
N,NN+19,-1.63,-0.42,-49.
N,NN+20,-1.63,-.52,-49
N,NN+21,-1.63,-0.64,-49.
N,NN+22,-1.73,-0.64,-49.
N,NN+23,-1.73,-0.52,-49.
N,NN+24,-1.84,-0.52,-49.
N,NN+28,-1.84,-2.0,-49.
FILL,NN+24,NN+28
N,NN+29,-2.06,-2.0,-49.
N,NN+33,-2.06,-.52,-49
FILL
N,NN+34,-2.06,-.42,-49
N,NN+35,-2.06,-.16,-49
N,NN+36,-2.06,0.0,-49.
N,NN+37,-1.84,0,-49
N,NN+39,-.93,0,-49
FILL
N,NN+40,-.83,0,-49
N,NN+41,-.51,0,-49
N,NN+42,-.38,0,-49
!OTHER SIDE
NDIV=14
NLST=NN+42*NDIV
N,NLST+1,0.0,0.0,0.0
N,NLST+2,0,-.16,-.16
N,NLST+3,0.0,-0.50,-0.50
N,NLST+4,-0.38,-0.50,-0.50
N,NLST+5,-.38,-.16,-.16
N,NLST+6,-0.51,-0.16,-0.16
N,NLST+7,-0.83,-0.16,-0.16
N,NLST+8,-.83,-.42,-.42
N,NLST+9,-0.83,-0.51,-0.51
N,NLST+10,-.93,-.51,-.51
N,NLST+11,-1.14,-0.51,-0.51
N,NLST+12,-1.14,-0.42,-0.42
N,NLST+13,-0.93,-0.42,-0.42
N,NLST+14,-0.93,-0.16,-0.16
N,NLST+16,-1.84,-0.16,-0.16
FILL
N,NLST+17,-1.84,-0.42,-0.42
N,NLST+18,-1.73,-.42,-.42
N,NLST+19,-1.63,-0.42,-0.42
N,NLST+20,-1.63,-.52,-.52
N,NLST+21,-1.63,-0.64,-0.64
N,NLST+22,-1.73,-0.64,-0.64
N,NLST+23,-1.73,-0.52,-0.52
N,NLST+24,-1.84,-0.52,-0.52
N,NLST+28,-1.84,-2.0,-2.0
FILL
N,NLST+29,-2.06,-2.0,-2.0
N,NLST+33,-2.06,-.52,-.52
FILL
N,NLST+34,-2.06,-.42,-.42
N,NLST+35,-2.06,-.16,-.16
N,NLST+36,-2.06,0.0,0.0
N,NLST+37,-1.84,0,0
N,NLST+39,-.93,0,0
FILL
N,NLST+40,-.83,0,0
N,NLST+41,-.51,0,0
N,NLST+42,-.38,0,0
FILL,NN+1,NLST+1,NDIV-1,,42
*REPEAT,42,1,1
*GET,EN1,ELEM,,NUM,MAX
E,NN+1,NN+2,NN+5,NN+42,NN+43,NN+44,NN+47,NN+84
E,NN+2,NN+3,NN+4,NN+5,NN+44,NN+45,NN+46,NN+47
E,NN+5,NN+6,NN+41,NN+42,NN+47,NN+48,NN+83,NN+84
E,NN+6,NN+7,NN+40,NN+41,NN+48,NN+49,NN+82,NN+83
E,NN+7,NN+14,NN+39,NN+40,NN+49,NN+56,NN+81,NN+82
E,NN+8,NN+13,NN+14,NN+7,NN+50,NN+55,NN+56,NN+49
E,NN+9,NN+10,NN+13,NN+8,NN+51,NN+52,NN+55,NN+50
E,NN+10,NN+11,NN+12,NN+13,NN+52,NN+53,NN+54,NN+55
E,NN+14,NN+15,NN+38,NN+39,NN+56,NN+57,NN+80,NN+81
E,NN+15,NN+16,NN+37,NN+38,NN+57,NN+58,NN+79,NN+80
E,NN+16,NN+35,NN+36,NN+37,NN+58,NN+77,NN+78,NN+79
E,NN+17,NN+34,NN+35,NN+16,NN+59,NN+76,NN+77,NN+58
E,NN+24,NN+33,NN+34,NN+17,NN+66,NN+75,NN+76,NN+59
E,NN+23,NN+24,NN+17,NN+18,NN+65,NN+66,NN+59,NN+60
E,NN+20,NN+23,NN+18,NN+19,NN+62,NN+65,NN+60,NN+61
E,NN+21,NN+22,NN+23,NN+20,NN+63,NN+64,NN+65,NN+62
E,NN+25,NN+32,NN+33,NN+24,NN+67,NN+74,NN+75,NN+66
E,NN+25,NN+26,NN+31,NN+32,NN+67,NN+68,NN+73,NN+74
E,NN+26,NN+27,NN+30,NN+31,NN+68,NN+69,NN+72,NN+73
E,NN+27,NN+28,NN+29,NN+30,NN+69,NN+70,NN+71,NN+72
*GET,EN2,ELEM,,NUM,MAX
EGEN,NDIV,42,EN1+1,EN2,1
```

Top Part 2:

```
/PREP7
ET,1,SOLID45
WPAVE,3.78,0,0
CSYS,WP
*GET,N1,NODE,,NUM,MAX
N,N2+20,-1.55,-.45,-.45
N,N2+21,-1.75,-0.45,-0.45
N,N2+22,-1.75,-0.35,-0.35
N,N2+23,-1.55,-0.35,-0.35
```

```
N,N1+1,0.0,0.0,-49.
N,N1+2,0.0,-0.12,-49.
N,N1+3,-0.25,-0.12,-49.
N,N1+4,-0.25,-0.35,-49.
N,N1+5,-0.125,-0.35,-49.
N,N1+6,-0.125,-0.45,-49.
N,N1+7,-.25,-.45,-49
N,N1+8,-.35,-.45,-49
N,N1+9,-0.475,-0.45,-49.
N,N1+10,-0.475,-0.35,-49.
N,N1+11,-0.35,-0.35,-49.
N,N1+12,-0.35,-0.12,-49.
N,N1+15,-1.45,-0.12,-49.
FILL
N,N1+16,-1.45,-0.35,-49.
N,N1+17,-1.25,-0.35,-49.
N,N1+18,-1.25,-0.45,-49.
N,N1+19,-1.45,-.45,-49
N,N1+20,-1.55,-.45,-49
N,N1+21,-1.75,-0.45,-49.
N,N1+22,-1.75,-0.35,-49.
N,N1+23,-1.55,-0.35,-49.
N,N1+24,-1.55,-0.12,-49.
N,N1+28,-3.52,-0.12,-49.
FILL
N,N1+29,-3.52,-0.32,-49.
N,N1+30,-3.02,-0.32,-49.
N,N1+31,-3.02,-0.45,-49.
N,N1+32,-3.52,-0.45,-49.
N,N1+33,-3.52,-0.71,-49.
N,N1+34,-3.02,-0.71,-49.
N,N1+35,-3.02,-0.84,-49.
N,N1+36,-3.52,-0.84,-49.
N,N1+37,-3.76,-0.91,-49.

N,N1+38,-4.31,-.91,-49
N,N1+39,-4.5,-0.91,-49.

N,N1+42,-4.5,-1.98,-49.
FILL
N,N1+45,-2.92,-1.98,-49.
FILL
N,N1+46,-2.92,-2.1,-49.
N,N1+49,-4.5,-2.1,-49
FILL
N,N1+50,-4.62,-2.1,-49
N,N1+51,-4.62,-1.98,-49
N,N1+54,-4.62,-.91,-49
FILL
N,N1+55,-4.62,-.75,-49
N,N1+57,-4.62,-0.16,-49.
FILL
N,N1+58,-4.31,-0.16,-49.
N,N1+60,-4.31,-0.75,-49.
FILL
N,N1+61,-3.76,-0.75,-49.
N,N1+62,-3.76,-.45,-49
N,N1+63,-3.76,-.32,-49
N,N1+64,-3.76,-.12,-49
N,N1+65,-3.76,0.0,-49.
N,N1+66,-3.52,0,-49
N,N1+70,-1.55,0,-49
FILL
N,N1+71,-1.45,0,-49
N,N1+74,-.35,0,-49
FILL
N,N1+75,-.25,0,-49
!OTHER SIDE
```

```
N,N2+24,-1.55,-0.12,-0.12
N,N2+28,-3.52,-0.12,-0.12
FILL
N,N2+29,-3.52,-0.32,-0.32
N,N2+30,-3.02,-0.32,-0.32
N,N2+31,-3.02,-0.45,-0.45
N,N2+32,-3.52,-0.45,-0.45
N,N2+33,-3.52,-0.71,-0.71
N,N2+34,-3.02,-0.71,-0.71

N,N2+35,-3.02,-0.84,-0.84
N,N2+36,-3.52,-0.84,-0.84
N,N2+37,-3.76,-0.91,-0.91
N2+38,-4.31,-.91,-.91
N,N2+39,-4.5,-0.91,-0.91
N,N2+42,-4.5,-1.98,-1.98
FILL
N,N2+45,-2.92,-1.98,-1.98
FILL
N,N2+46,-2.92,-2.1,-2.1
N2+49,-4.5,-2.1,-2.1
FILL
N,N2+50,-4.62,-2.1,-2.1
N,N2+51,-4.62,-1.98,-1.98
N,N2+54,-4.62,-.91,-.91
FILL
N,N2+55,-4.62,-.75,-.75
N,N2+57,-4.62,-0.16,-0.16
FILL
N,N2+58,-4.31,-0.16,-0.16
N,N2+60,-4.31,-0.75,-0.75
FILL
N,N2+61,-3.76,-0.75,-0.75
N,N2+62,-3.76,-.45,-.45
N,N2+63,-3.76,-.32,-.32
N,N2+64,-3.76,-.12,-.12
N,N2+65,-3.76,0.0,0.0
N,N2+66,-3.52,0,0
N,N2+70,-1.55,0,0
FILL
N,N2+71,-1.45,0,0
N,N2+74,-.35,0,0
FILL
N,N2+75,-.25,0,0
! NOW FILL
FILL,N1+1,N2+1,NDIV-1,,75
*REPEAT,75,1,1
*GET,EN1,ELEM,,NUM,MAX
E,N1+1,N1+2,N1+3,N1+75,N1+76,N1+77,N1+78,N1+150
E,N1+3,N1+12,N1+74,N1+75,N1+78,N1+87,N1+149,N1+150
E,N1+3,N1+4,N1+11,N1+12,N1+78,N1+79,N1+86,N1+87
E,N1+5,N1+6,N1+7,N1+4,N1+80,N1+81,N1+82,N1+79
E,N1+7,N1+8,N1+11,N1+4,N1+82,N1+83,N1+86,N1+79
E,N1+8,N1+9,N1+10,N1+11,N1+83,N1+84,N1+85,N1+86
E,N1+12,N1+13,N1+73,N1+74,N1+87,N1+88,N1+148,N1+149
E,N1+13,N1+14,N1+72,N1+73,N1+88,N1+89,N1+147,N1+148
E,N1+14,N1+15,N1+71,N1+72,N1+89,N1+90,N1+146,N1+147
E,N1+15,N1+24,N1+70,N1+71,N1+90,N1+99,N1+145,N1+146
E,N1+15,N1+16,N1+23,N1+24,N1+90,N1+91,N1+98,N1+99
E,N1+17,N1+18,N1+19,N1+16,N1+92,N1+93,N1+94,N1+91
E,N1+16,N1+19,N1+20,N1+23,N1+91,N1+94,N1+95,N1+98
E,N1+20,N1+21,N1+22,N1+23,N1+95,N1+96,N1+97,N1+98
E,N1+24,N1+25,N1+69,N1+70,N1+99,N1+100,N1+144,N1+145
E,N1+25,N1+26,N1+68,N1+69,N1+100,N1+101,N1+143,N1+144
E,N1+26,N1+27,N1+67,N1+68,N1+101,N1+102,N1+142,N1+143
E,N1+27,N1+28,N1+66,N1+67,N1+102,N1+103,N1+141,N1+142
E,N1+28,N1+64,N1+65,N1+66,N1+103,N1+139,N1+140,N1+141
E,N1+29,N1+63,N1+64,N1+28,N1+104,N1+138,N1+139,N1+103
```

NDIV=14 N2=N1+75*NDIV N,N2+1,0.0,0.0,0.0 N,N2+2,0.0,-0.12,-0.12 N,N2+3,-0.25,-0.12,-0.12 N,N2+4,-0.25,-0.35,-0.35 N,N2+5,-0.125,-0.35,-0.35 N,N2+6,-0.125,-0.45,-0.45 N,N2+7,-.25,-.45,-.45 N,N2+8,-.35,-.45,-.45 N,N2+9,-0.475,-0.45,-0.45 N,N2+10,-0.475,-0.35,-0.35 N,N2+11,-0.35,-0.35,-0.35 N,N2+12,-0.35,-0.12,-0.12 N,N2+15,-1.45,-0.12,-0.12 FILL N,N2+16,-1.45,-0.35,-0.35 N,N2+17,-1.25,-0.35,-0.35 N,N2+18,-1.25,-0.45,-0.45 N,N2+19,-1.45,-.45,-.45	E,N1+29,N1+32,N1+62,N1+63,N1+104,N1+107,N1+137,N1+138 E,N1+30,N1+31,N1+32,N1+29,N1+105,N1+106,N1+107,N1+104 E,N1+32,N1+33,N1+61,N1+62,N1+107,N1+108,N1+136,N1+137 E,N1+33,N1+36,N1+37,N1+61,N1+108,N1+111,N1+112,N1+136 E,N1+34,N1+35,N1+36,N1+33,N1+109,N1+110,N1+111,N1+108 E,N1+61,N1+37,N1+38,N1+60,N1+136,N1+112,N1+113,N1+135 E,N1+38,N1+39,N1+60,N1+60,N1+113,N1+114,N1+135,N1+135 E,N1+60,N1+39,N1+54,N1+55,N1+135,N1+114,N1+129,N1+130 E,N1+39,N1+40,N1+53,N1+54,N1+114,N1+115,N1+128,N1+129 E,N1+40,N1+41,N1+52,N1+53,N1+115,N1+116,N1+127,N1+128 E,N1+41,N1+42,N1+51,N1+52,N1+116,N1+117,N1+126,N1+127 E,N1+42,N1+49,N1+50,N1+51,N1+117,N1+124,N1+125,N1+126 E,N1+42,N1+43,N1+48,N1+49,N1+117,N1+118,N1+123,N1+124 E,N1+43,N1+44,N1+47,N1+48,N1+118,N1+119,N1+122,N1+123 E,N1+44,N1+45,N1+46,N1+47,N1+119,N1+120,N1+121,N1+122 E,N1+60,N1+55,N1+56,N1+59,N1+135,N1+130,N1+131,N1+134 E,N1+59,N1+56,N1+57,N1+58,N1+134,N1+131,N1+132,N1+133 *GET,EN2,ELEM,,NUM,MAX EGEN,NDIV,75,EN1+1,EN2,1

A.2 Text files for control volume and pressure distribution

50"x144" model:

```
HZ=72
HY=52
HX=12
NVERT=20
NHOR=20
DHZ=HZ/NHOR
AISP=100*1.4666*12 ! IN FT/SEC, 100 IN MPH
/PREP7
ET,1,SOLID70
MP,KXX,1,1
BLC4,0,0,5*HX,5*HY,5*HZ
BLC4,0,0,HX,HY,HZ
VGEN,2,2,,,2*HX,,,,,1
VSBV,1,2
ASEL,S,LOC,X,0
SFA,ALL,1,HFLUX,AISP
ASEL,ALL
ASEL,S,LOC,X,5*HX
SFA,ALL,1,HFLUX,-AISP
ASEL,ALL
ASEL,S,LOC,Z,0
SFA,ALL,1,HFLUX,0
ASEL,ALL
NUMCMP,VOLU
SMRTSIZE,2
MSHKEY,0
MSHAPE,1
VMESH,1
FINISH
/SOLU
SOLVE
FINISH
/post1
XHZ=DHZ*0
PATH,P1,2,,NVERT
PPATH,1,,2*DX,0,XHZ
PPATH,2,,2*DX,HY,XHZ
PDEF,VELP1,TF,SUM
/OUTPUT,PSOUT,DAT
PRPATH,VELP1
/OUTPUT
```

```
*DO,I,1,NHOR
XHZ=DHZ*I
PATH,P2,2,,NVERT
PPATH,1,,2*DX,0,XHZ
PPATH,2,,2*DX,HY,XHZ
PDEF,VELP2,TF,SUM
/OUTPUT,PSOUT,DAT,,APPEND
PRPATH,VELP2
/OUTPUT
*ENDDO
```

122"x98" model:

```
HZ=49
HY=134
HX=12
NVERT=30
NHOR=14
DHZ=HZ/NHOR
AISP=100*1.4666*12 ! IN FT/SEC, 100 IN MPH
/PREP7
ET,1,SOLID70
MP,KXX,1,1
BLC4,0,0,5*HX,5*HY,5*HZ
BLC4,0,0,HX,HY,HZ
VGEN,2,2,,,2*HX,,,,,1
VSBV,1,2
ASEL,S,LOC,X,0
SFA,ALL,1,HFLUX,AISP
ASEL,ALL
ASEL,S,LOC,X,5*HX
SFA,ALL,1,HFLUX,-AISP
ASEL,ALL
ASEL,S,LOC,Z,0
SFA,ALL,1,HFLUX,0
ASEL,ALL
NUMCMP,VOLU
SMRTSIZE,2
MSHKEY,0
MSHAPE,1
VMESH,1
FINISH
/SOLU
SOLVE
FINISH
/post1
XHZ=DHZ*0
PATH,P1,2,,NVERT
PPATH,1,,2*DX,0,XHZ
PPATH,2,,2*DX,HY,XHZ
PDEF,VELP1,TF,SUM
/OUTPUT,PRESO,DAT
PRPATH,VELP1
/OUTPUT
*DO,I,1,NHOR
XHZ=DHZ*I
PATH,P2,2,,NVERT
PPATH,1,,2*DX,0,XHZ
PPATH,2,,2*DX,HY,XHZ
PDEF,VELP2,TF,SUM
/OUTPUT,PRESO,DAT,,APPEND
PRPATH,VELP2
/OUTPUT
*ENDDO
```

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